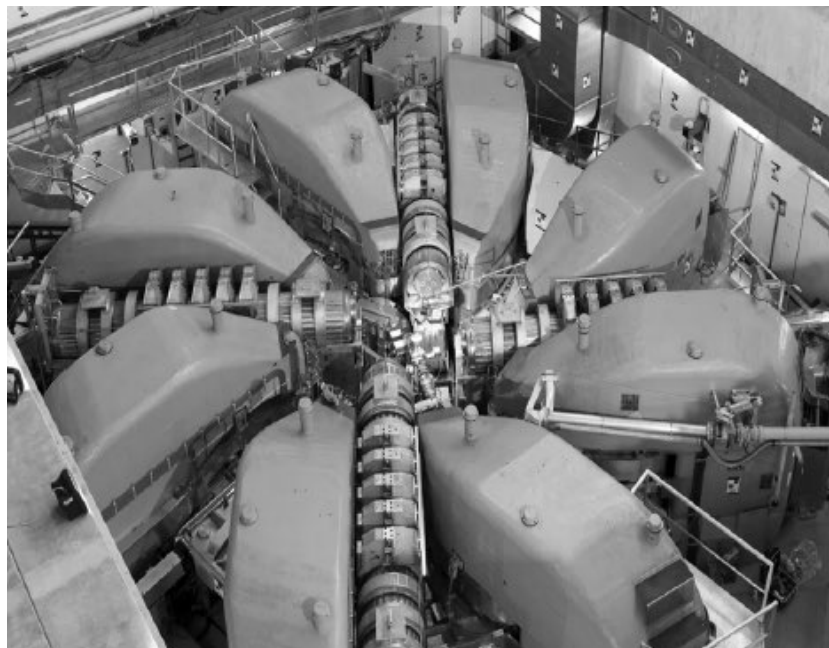




PSI muon beam lines and future developments

Angela Papa, Paul Scherrer Institut and University of Pisa/INFN On behalf of the HiMB and muCool group
Snowmass Committee meeting, New accelerator concepts for high intensity muon beams session (virtual meeting)
SCM 2020, Oct 5th - Oct 8th



Outline

- The High Intensity Muon Beam project at PSI (HiMB)
- Towards High-Brightness low energy muon beams (muCool)

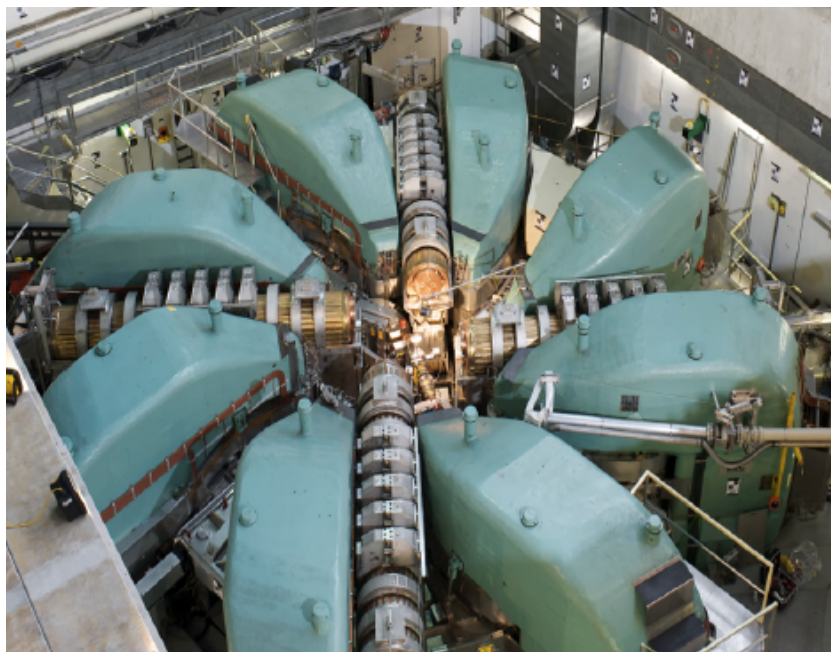
HiMB motivations

- Aim: $O(10^{10})$ muon/s; Surface (positive) muon beam ($p = 28 \text{ MeV}/c$); **DC** beam
- Time schedule: **O(2025)**
- PSI delivers the highest intensity DC μ^+ beam:
 $5 \times 10^8 \mu^+/s$
- Next generation cLFV experiments require higher muon rates
- New opportunities for future muon (particle physics) based experiments
- New opportunities for μ SR experiments
- Different experiments demand for a variety of beam characteristics:
 - DC vs pulsed
 - Momentum depends on applications: stopped beams require low momenta
- Here focus on **DC low momenta muon beams**
- Maintain PSI leadership in DC low momentum high intensity muon beams



The world's most intense continuous muon beam

- PSI delivers the most intense continuous low momentum muon beam in the world (**Intensity Frontiers**)
 - Intensity = 5×10^8 muon/s, low momentum $p = 28$ MeV/c



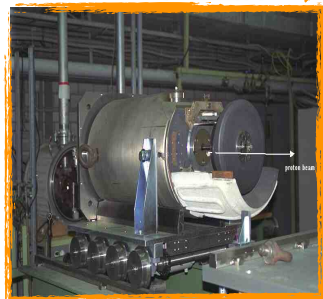
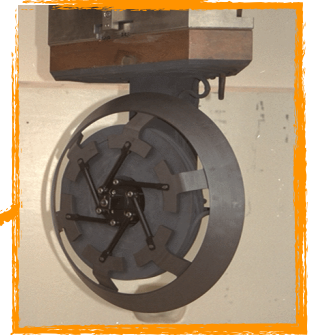
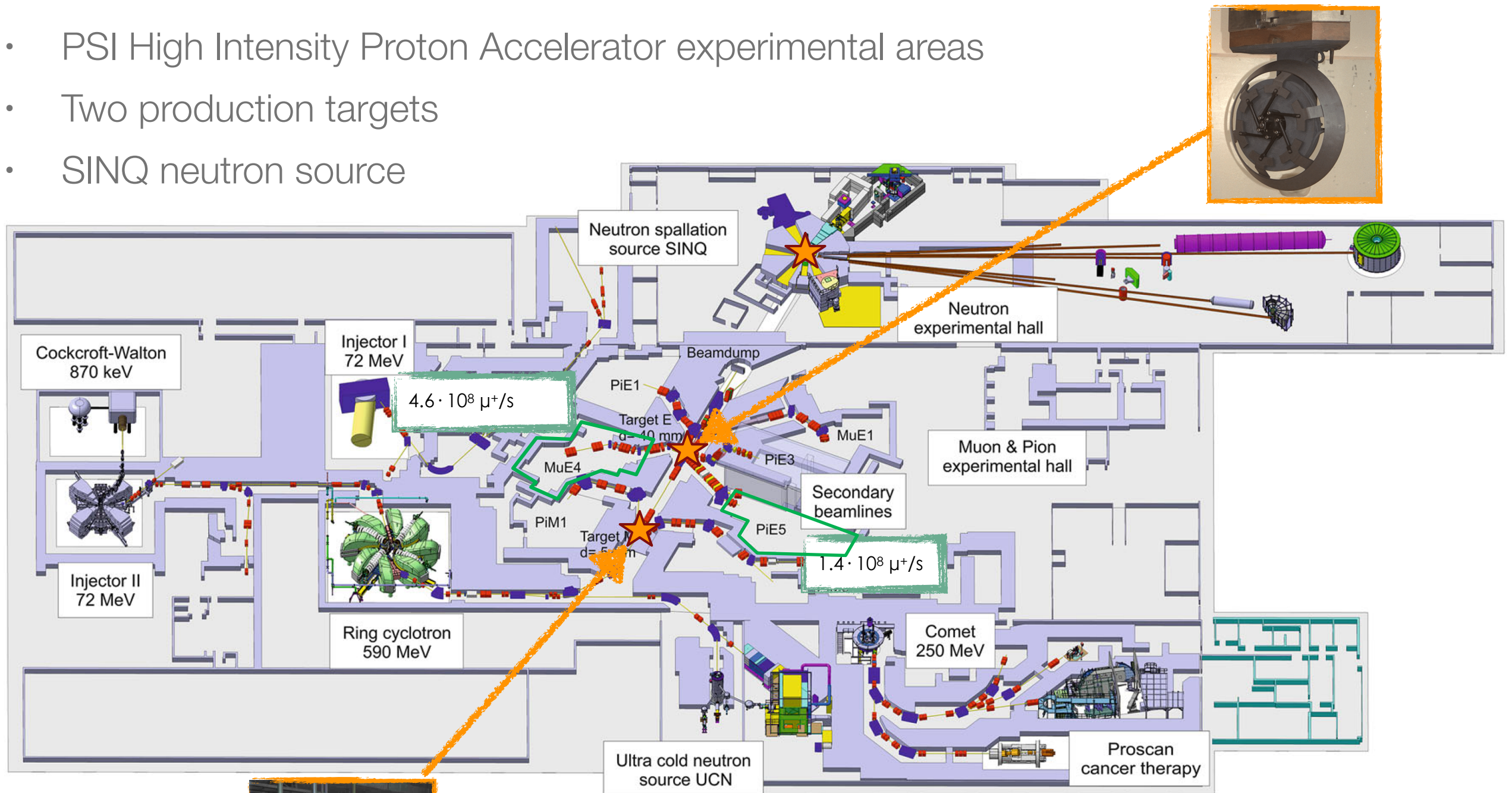
590 MeV proton ring cyclotron
Time structure: 50 MHz/20 ns
Power: 1.4 MW

PSI landscape



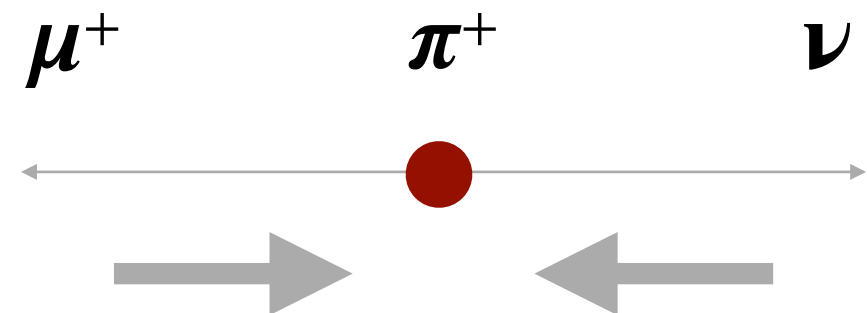
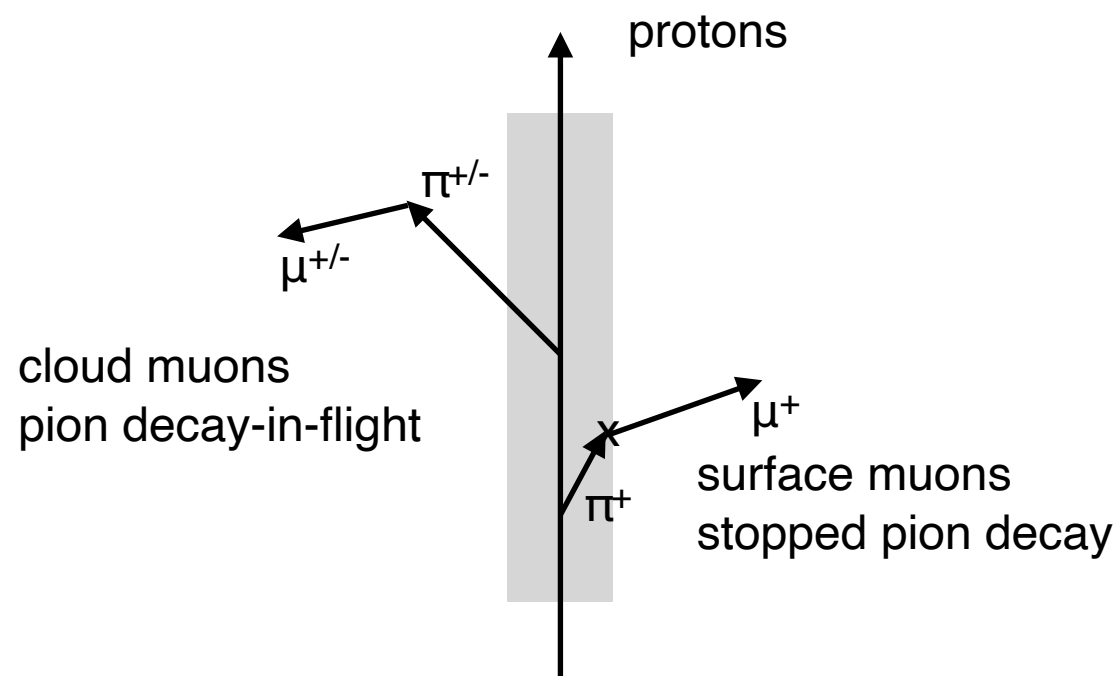
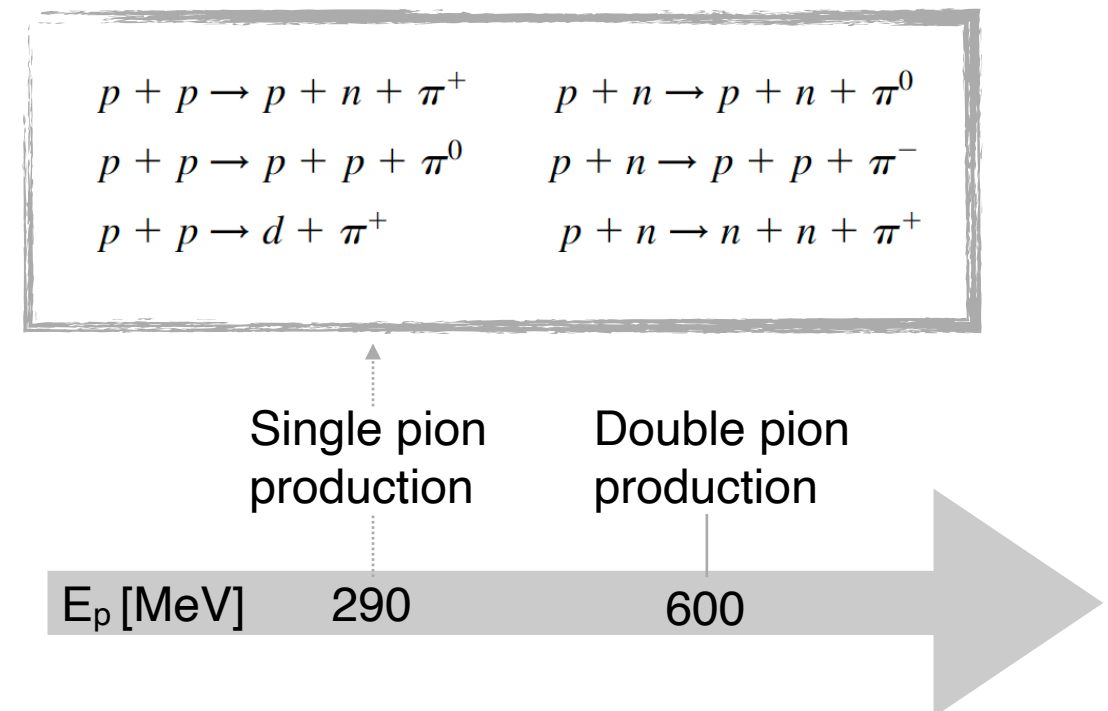
The world's most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas
- Two production targets
- SINQ neutron source

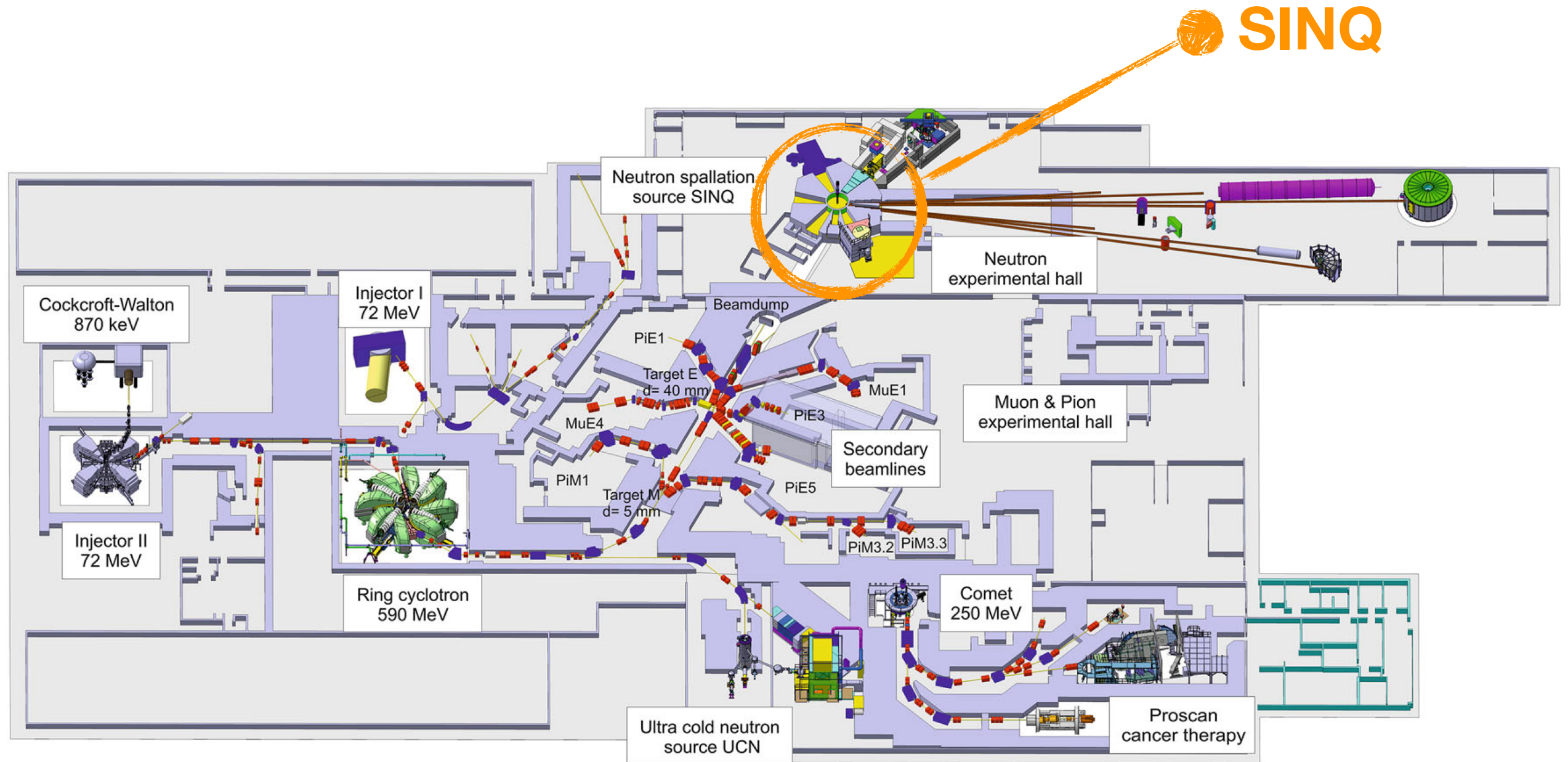


Muon production via pion decay

- Single pion production at 290 MeV proton energy (LAB)
- Low-energy muon beam lines typically tuned to surface- μ^+ at ~ 28 MeV/c
- Note: surface- $\mu \rightarrow$ polarized positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons



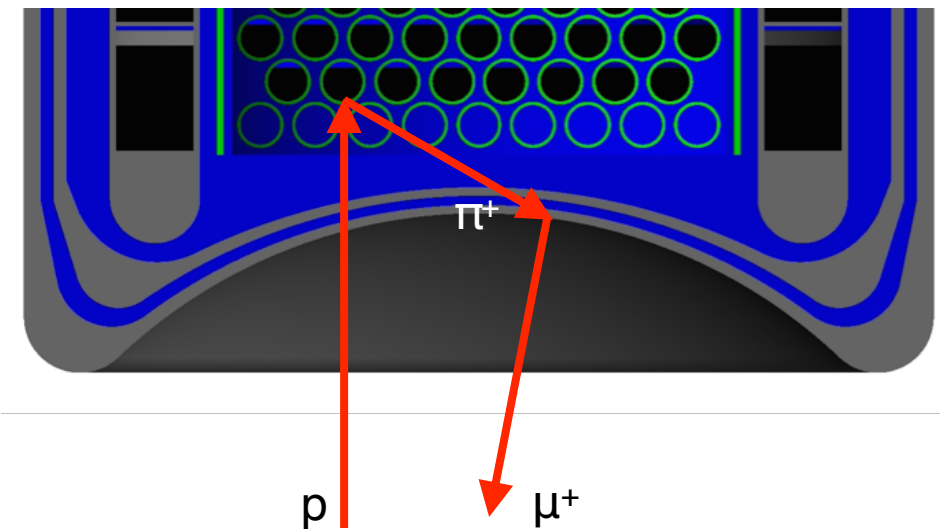
Initial HiMB concept: @SINQ



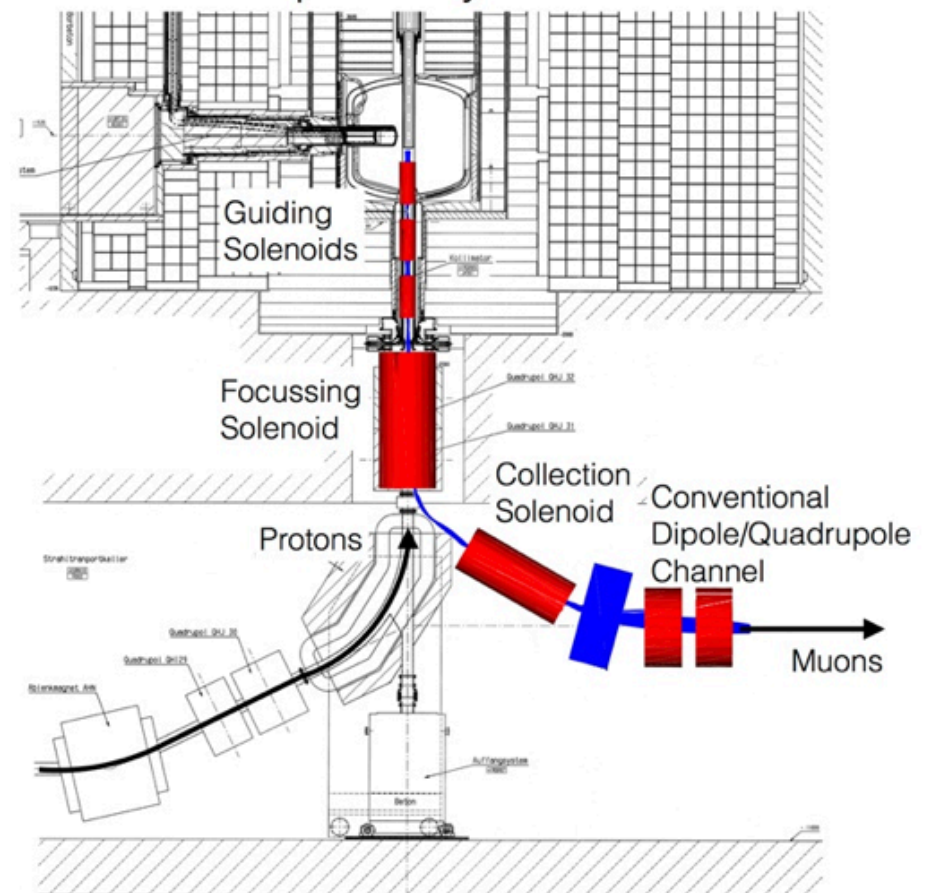
Initial HiMB concept: @SINQ

- Source simulation (below safety window):
 9×10^{10} surface- μ^+ /s @ 1.7 mA I_p
- Profit from stopping of full beam
- Residual proton beam (~ 1 MW) dumped on SINQ
- Replace existing quadrupoles with solenoids:
 - Preserve proton beam footprint
 - Capture backward travelling surface muons
- Extract muons in Dipole fringe field
- Backward travelling pions stopped in beam window
- Capturing turned out to be difficult :
 - Large phase space (divergence & 'source' extent)
 - Capture solenoid aperture needed to be increased, but constrained by moderator tank
- High radiation level close to target
- Due these constraints and after several iterations with different capturing elements:
 - **Not enough captures muons to make an high intensity beam**
 - **Alternative solution: HiMB @ EH**

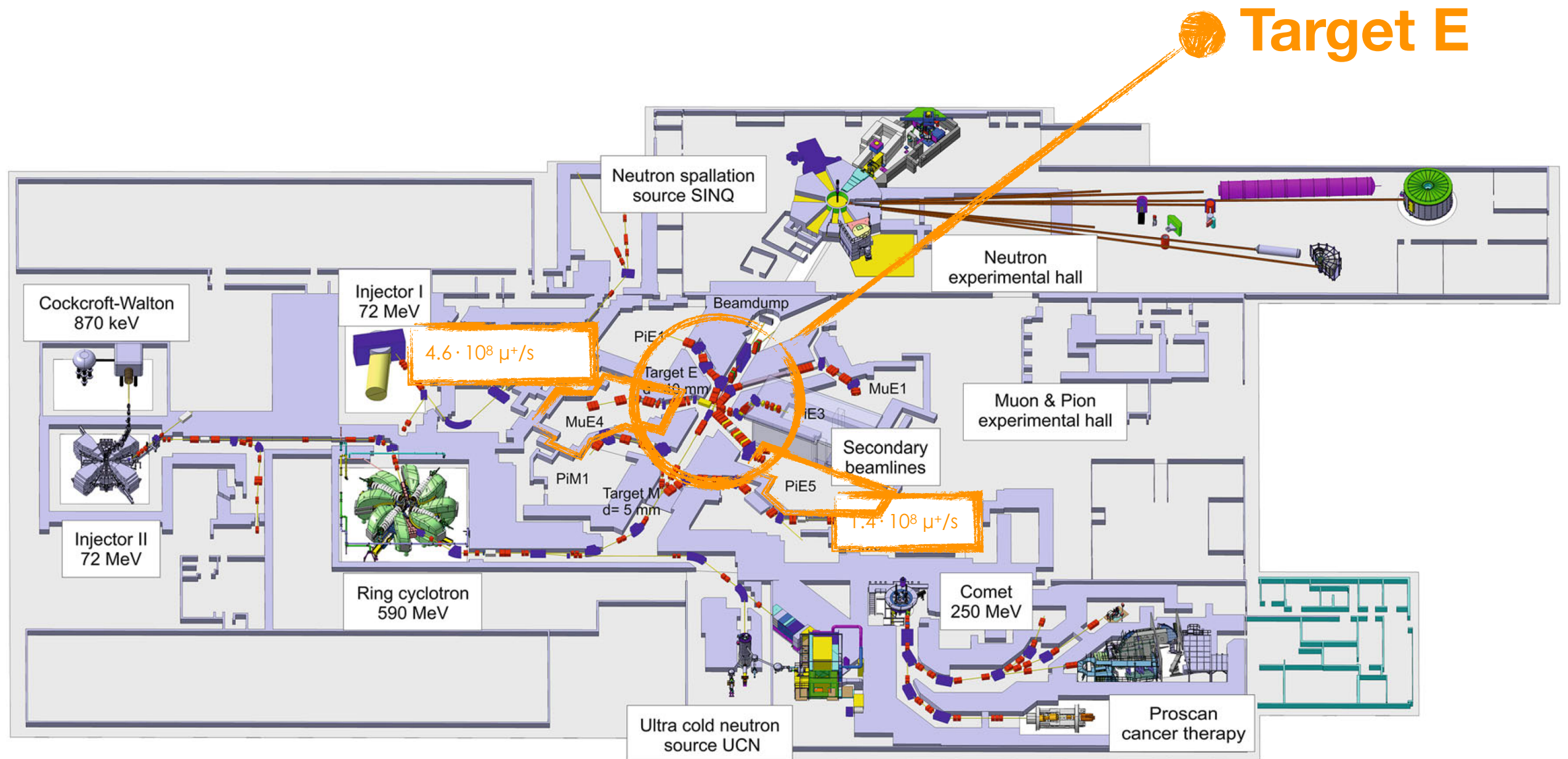
SINQ spallation target



HiMB Conceptual Layout

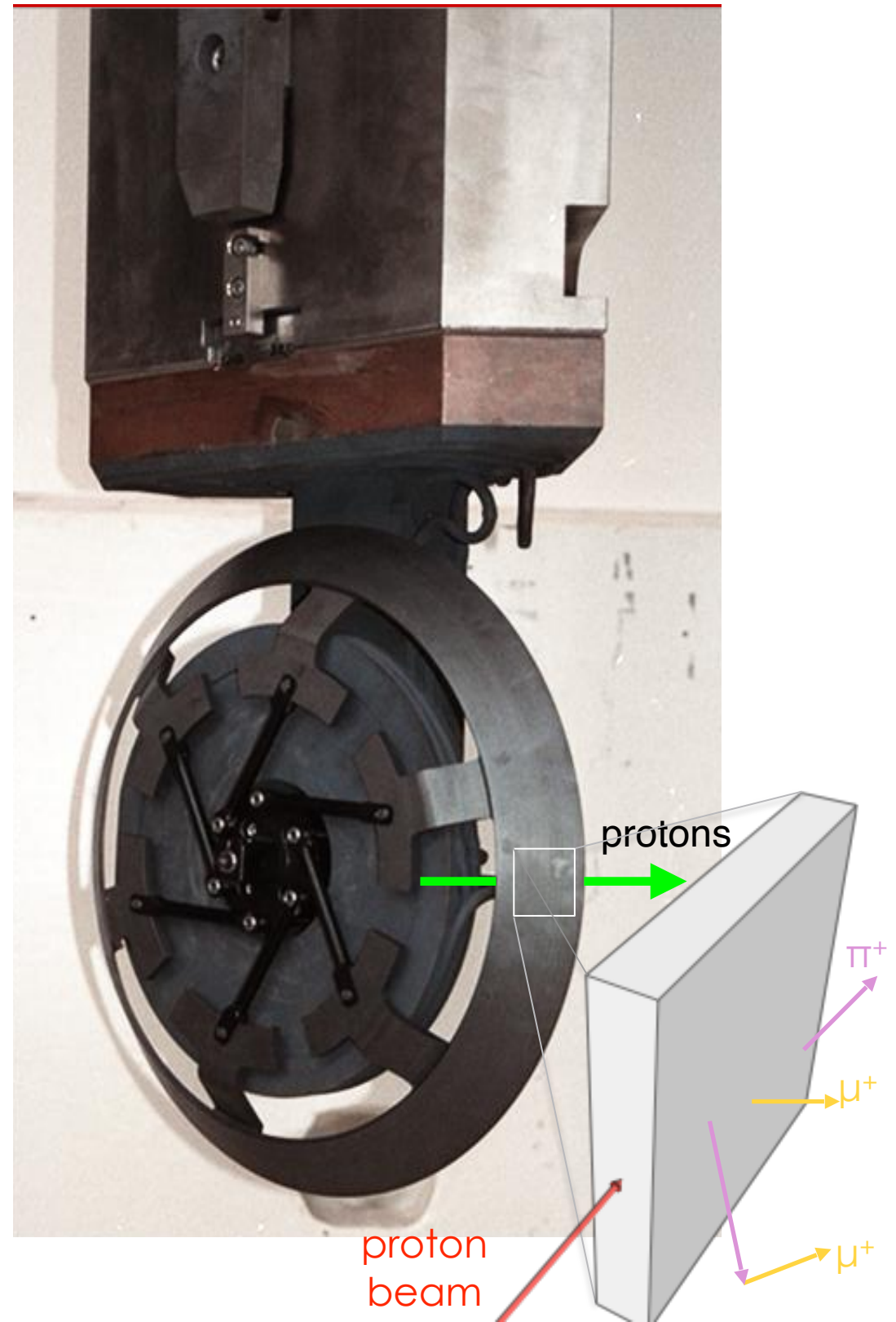


High Muon Beam Intensity: @Main Experimental Hall



Target E

- Rotating target (1 Hz)
- Polycrystalline graphite
- 40 mm length in beam direction
- 50 kW proton beam energy deposit
- 1700 K radiation cooled
- 30 % loss of protons
- Delivers world most intense surface muon beams

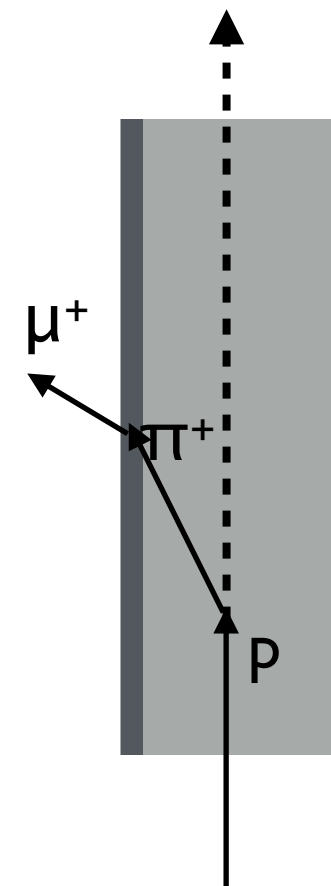


HiMB @ HE

- Back to standard target to exploit possible improvements towards high intensity beams:
 - Target
 - alternate materials
 - geometry
- Beam line
 - high capture efficiency
 - large phase space acceptance transport channel

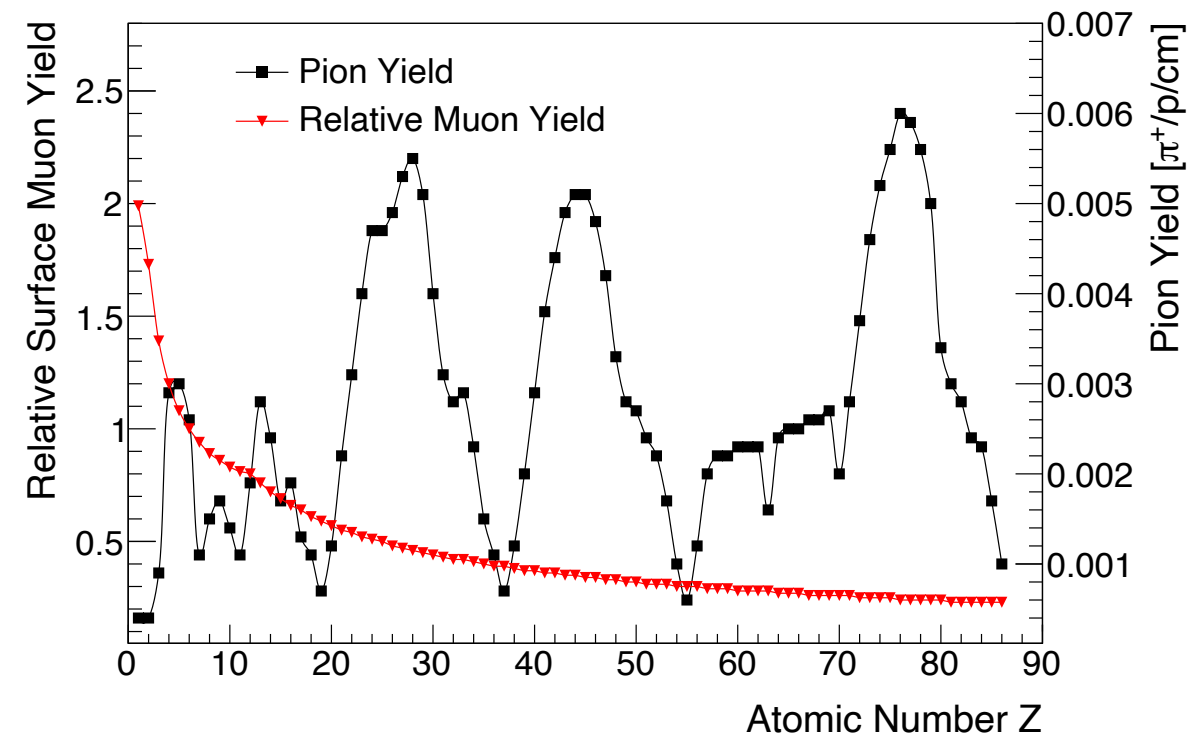
Optimization of standard production targets

- Back to standard target to exploit possible improvements towards high intensity beams
- **Target alternate materials**
 - Search for high pion yield materials -> higher muon yield
 - Several materials have pion yields > 2x Carbon
 - Relative muon yield favours low-Z materials, but difficult to construct as a target
 - B₄C and Be₂C show 10-15% gain



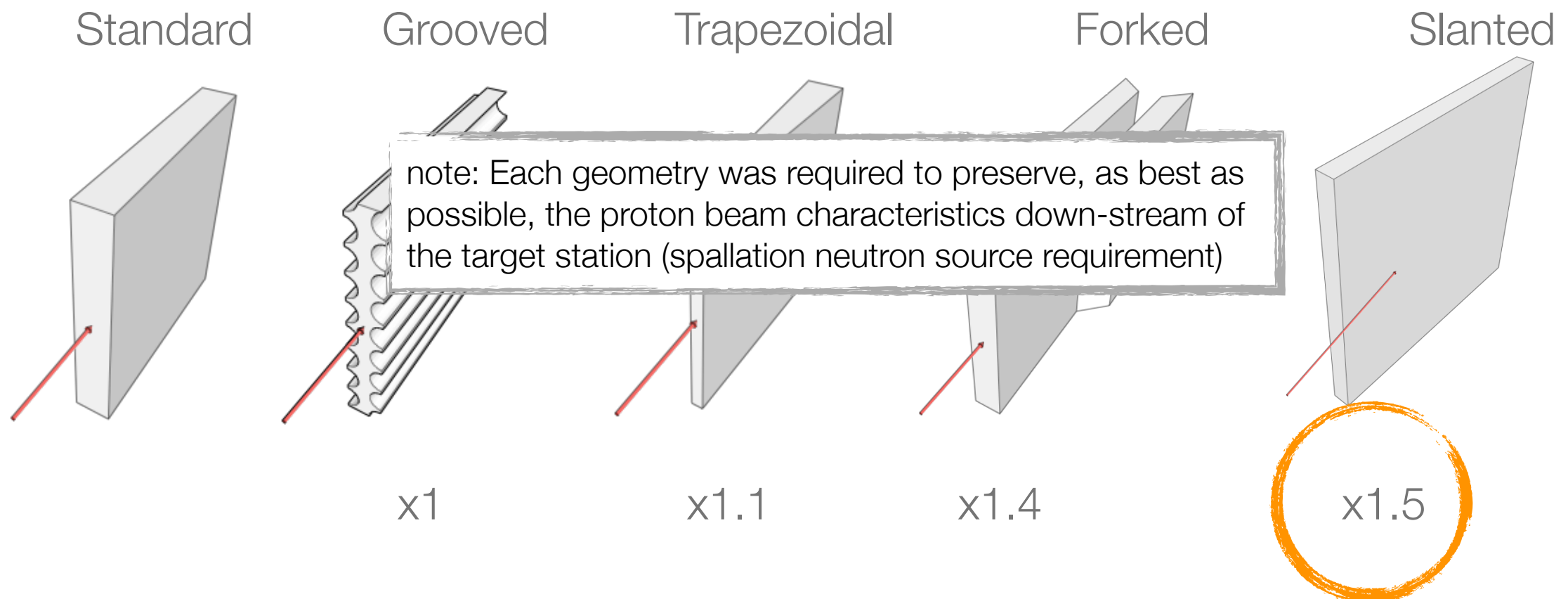
$$\text{relative } \mu^+ \text{ yield} \propto \pi^+ \text{ stop density} \cdot \mu^+ \text{ Range} \cdot \text{length}$$

$$\begin{aligned} &\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_c (6/12)_c}{\rho_x (Z/A)_x} \\ &\propto Z^{1/3} \cdot Z \cdot \left(\frac{1}{Z}\right) \cdot \left(\frac{1}{Z}\right) \\ &\propto \frac{1}{Z^{2/3}} \end{aligned}$$



Optimization of standard production targets

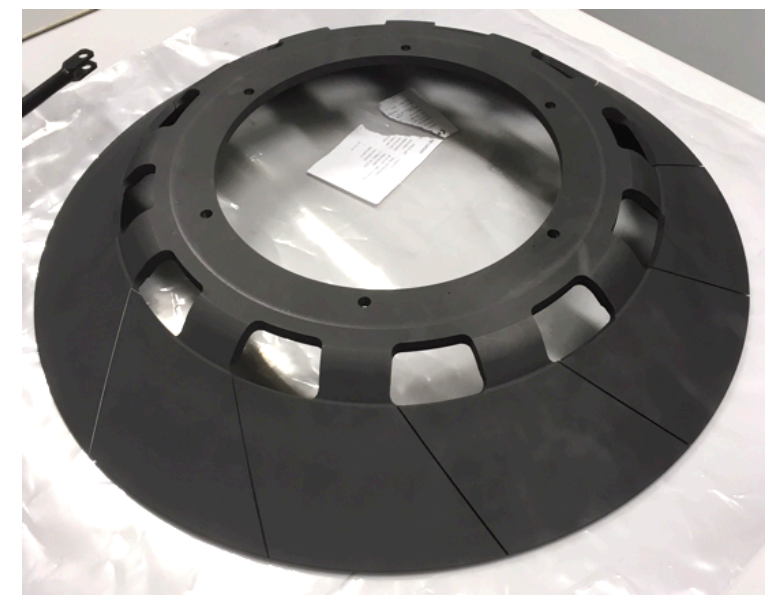
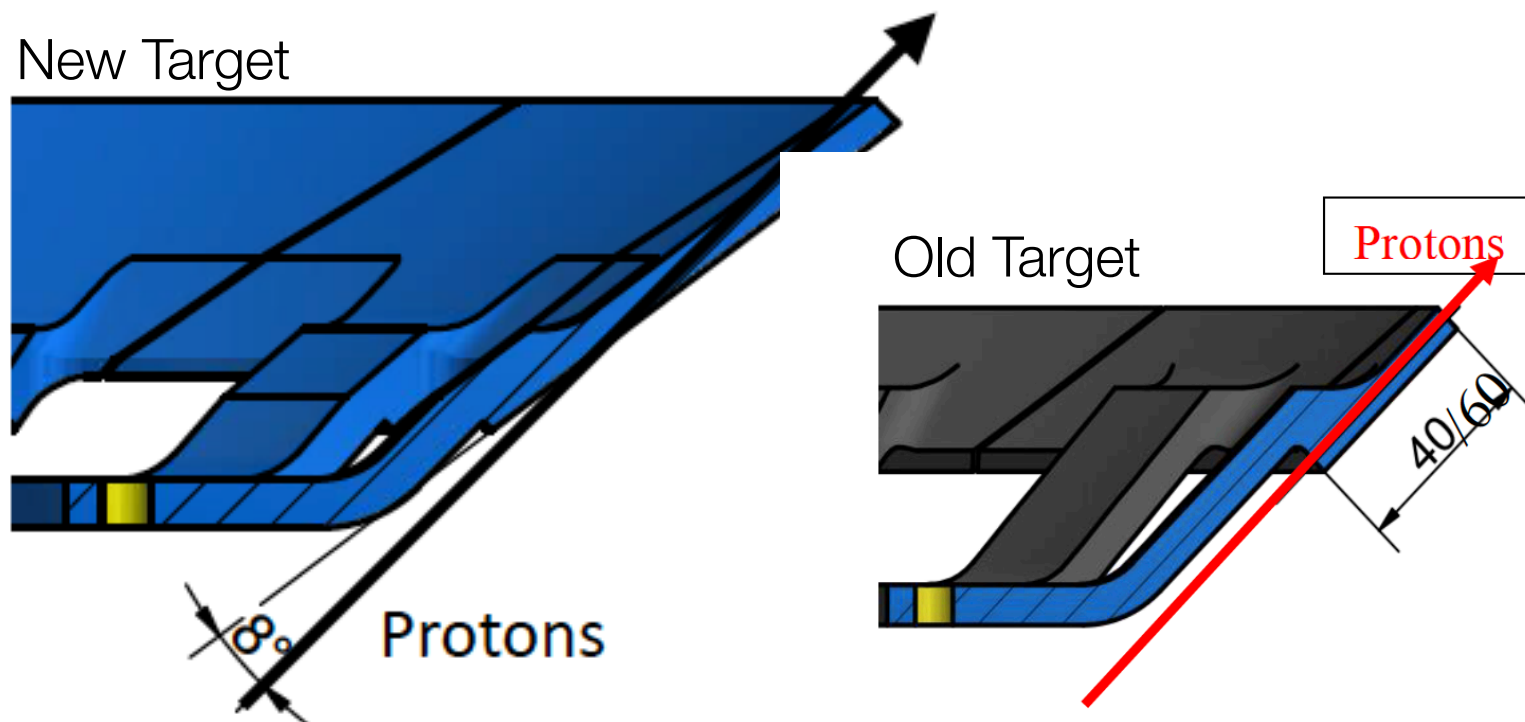
- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface
- **Target geometry**
 - Comparison studies of different target geometries: **Different shapes and rotation angles**
 - Enhancements normalised to standard target



Slanted target: towards the test

Prototype for the New Target E

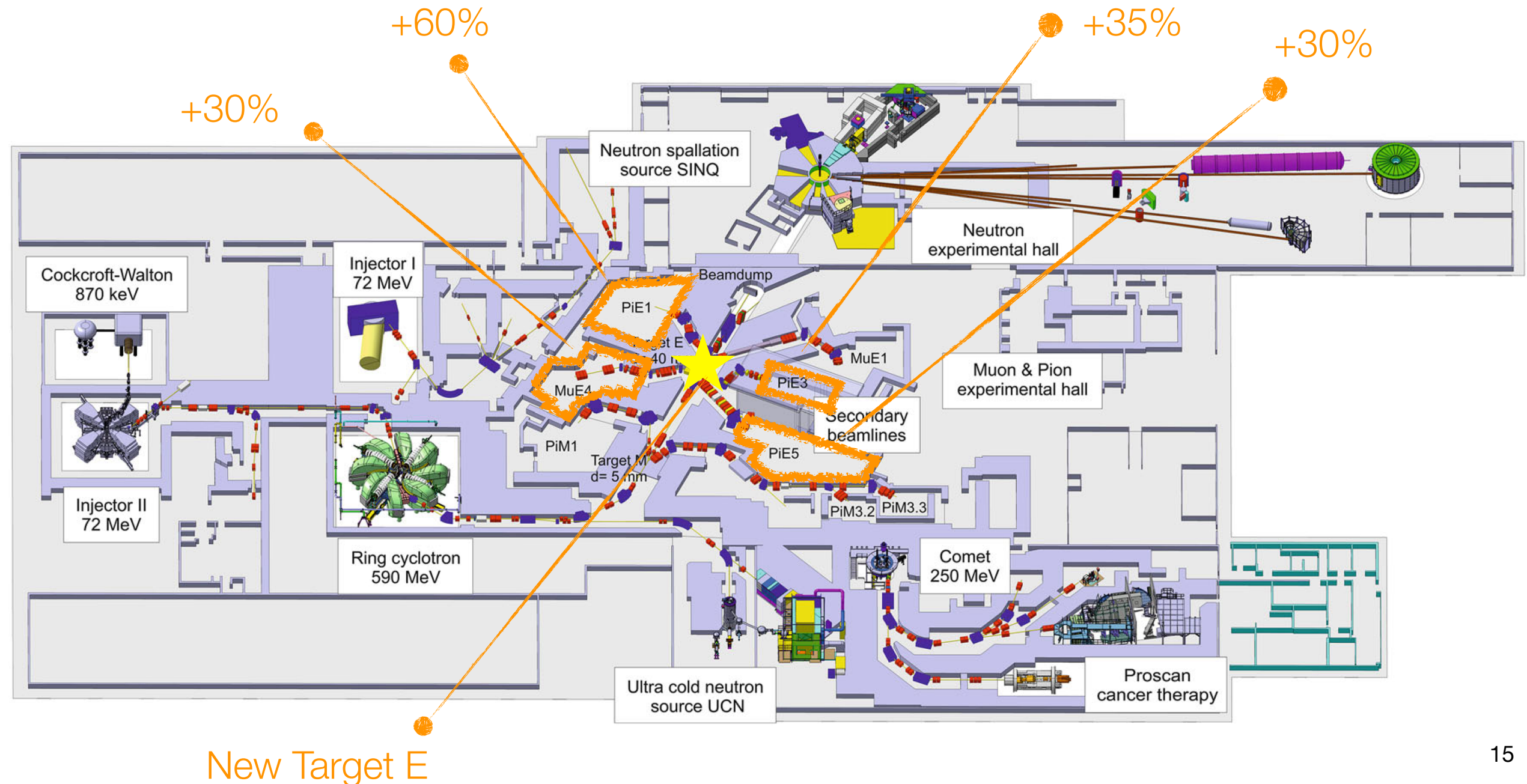
- Upgrade existing graphite production target E 40 mm
 - 8° slanting angle: Measurement in forward / backward / sideways direction
 - Production and implementation feasible
 - Mechanical and thermal simulations completed and no show-stopper found
 - **Installed in week 48 (Nov. 25th, 2019)**
- **Goals**
 - **Increase surface muon rates for all connected beam lines**
 - **Increase safety margin for “missing” target with the proton beam**



New Target E

Slanted target: 2019 test Results

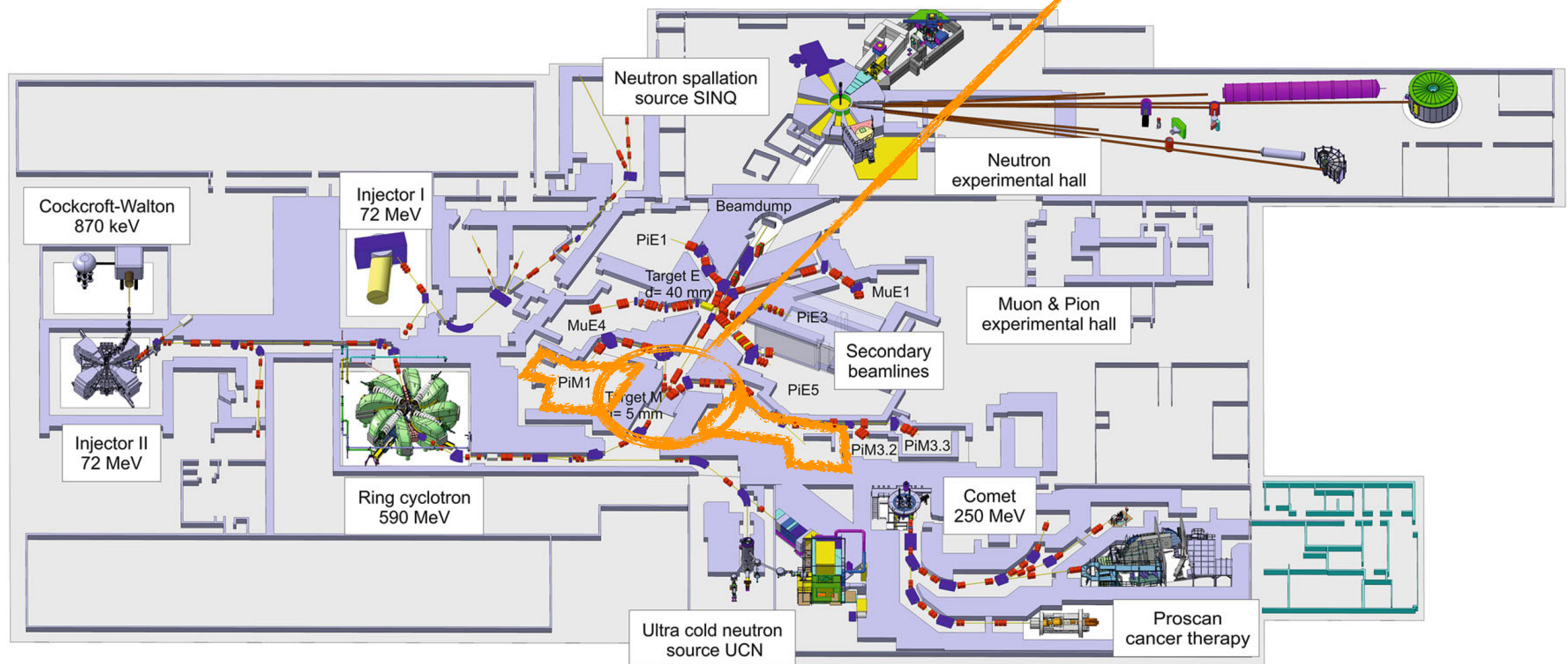
- Expect ~30-60 % enhancement
- Measurements successfully done in different experimental areas in fall 2019
- Analysis still undergoing: **increased muon yield CONFIRMED!**
- To be seen: **impact of higher thermal stress on long term stability of target wheel**



Towards the HiMB project @ PSI

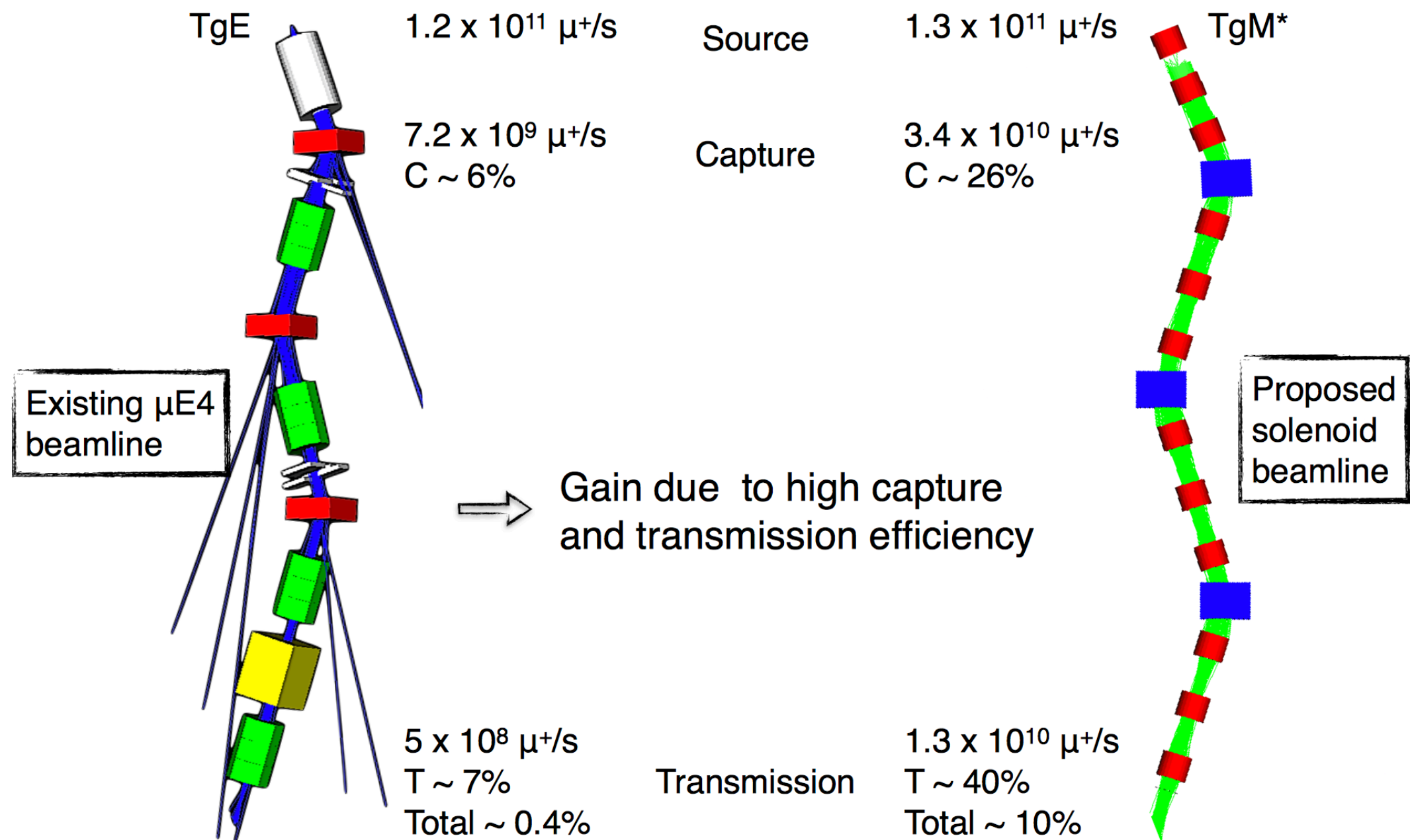
- Final position for the HiMB target: “Present” TgM location
- $\sim 90^\circ$ extraction to existing experimental areas
- Large phase space acceptance solenoidal channel

Target M



Prospects

- Aim: $O(10^{10})$ muon/s; Surface (positive) muon beam ($p = 28 \text{ MeV/c}$); **DC** beam
- Time schedule: **O(2025)**



The muCool project at PSI

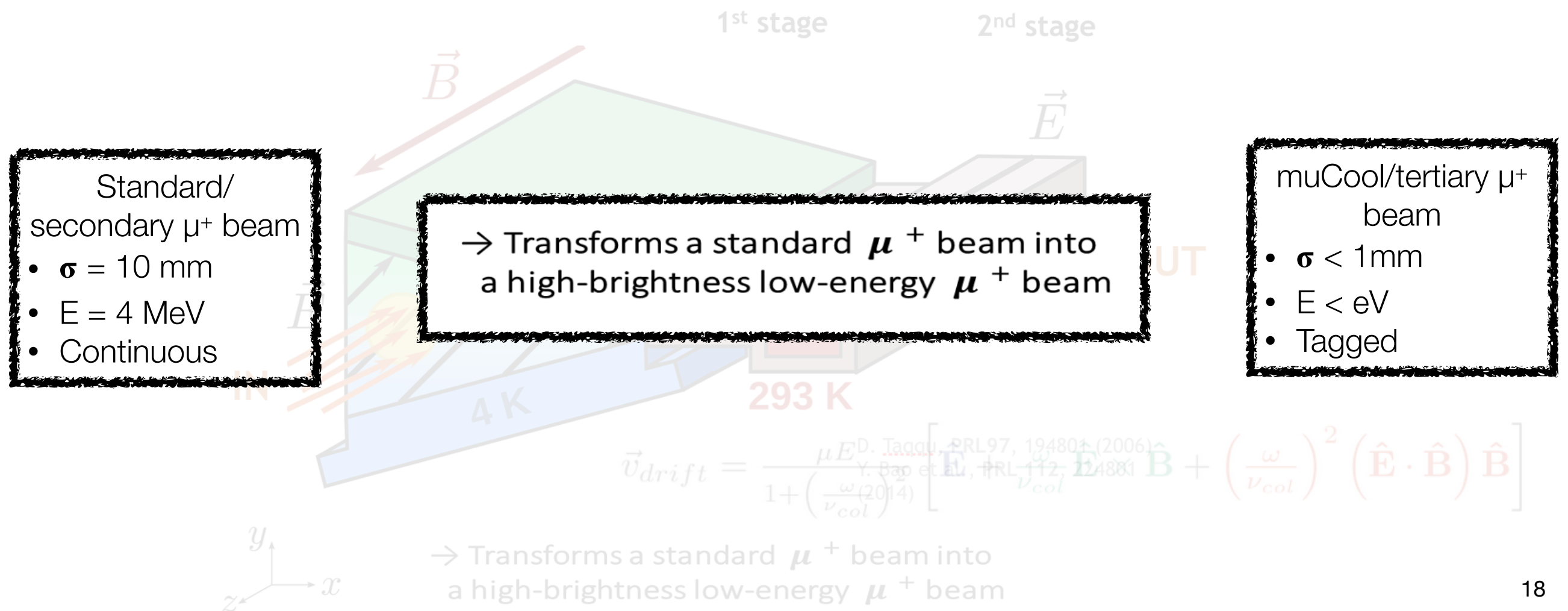
- Aim: High-brightness low energy muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor 10^{10} with an efficiency of 10^{-3}

for:

μ SR (solid state physics)

muonium (spectroscopy, gravitational interaction...)

muon experiments (μ EDM, g-2...)



The muCool project at PSI

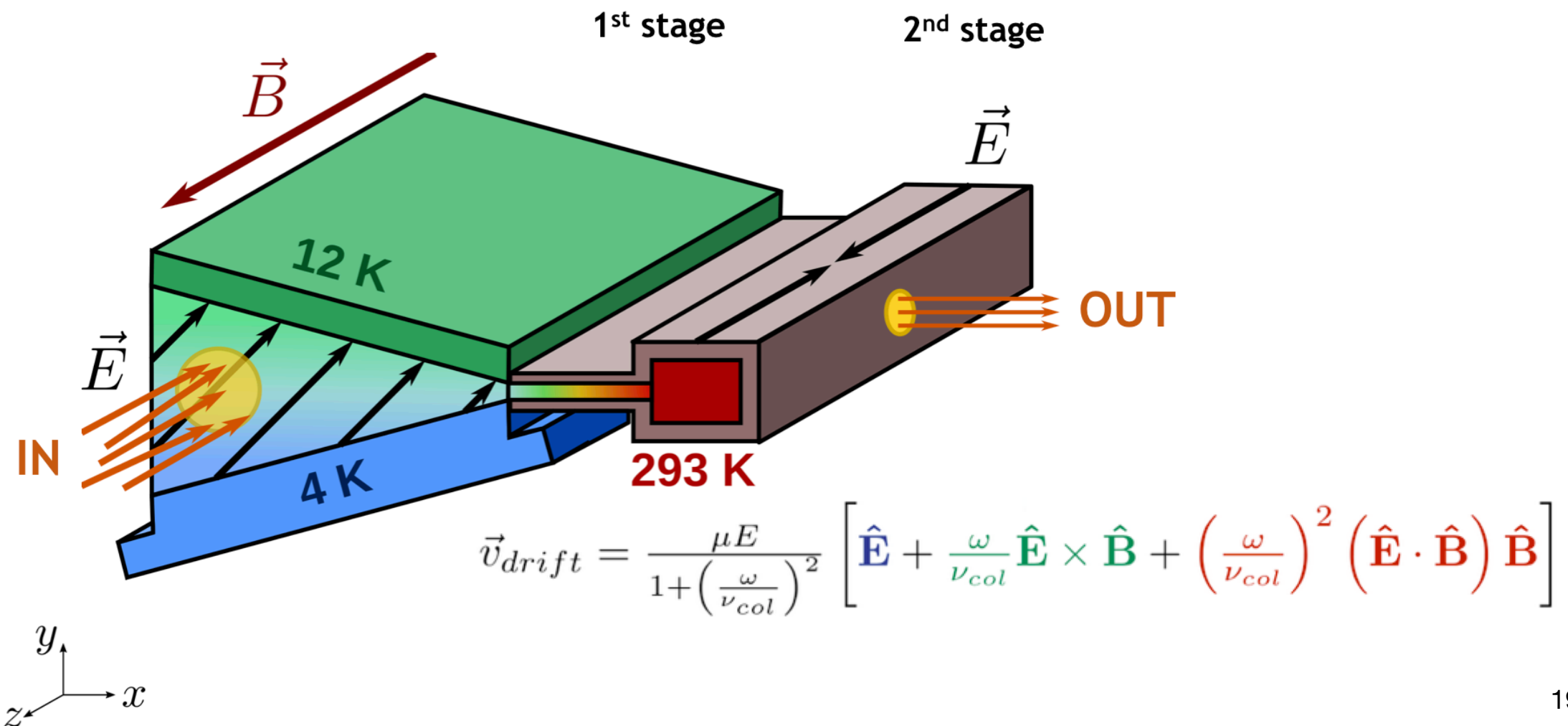
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- Increase in brightness by a factor 10^{10} with an efficiency of 10^{-3}

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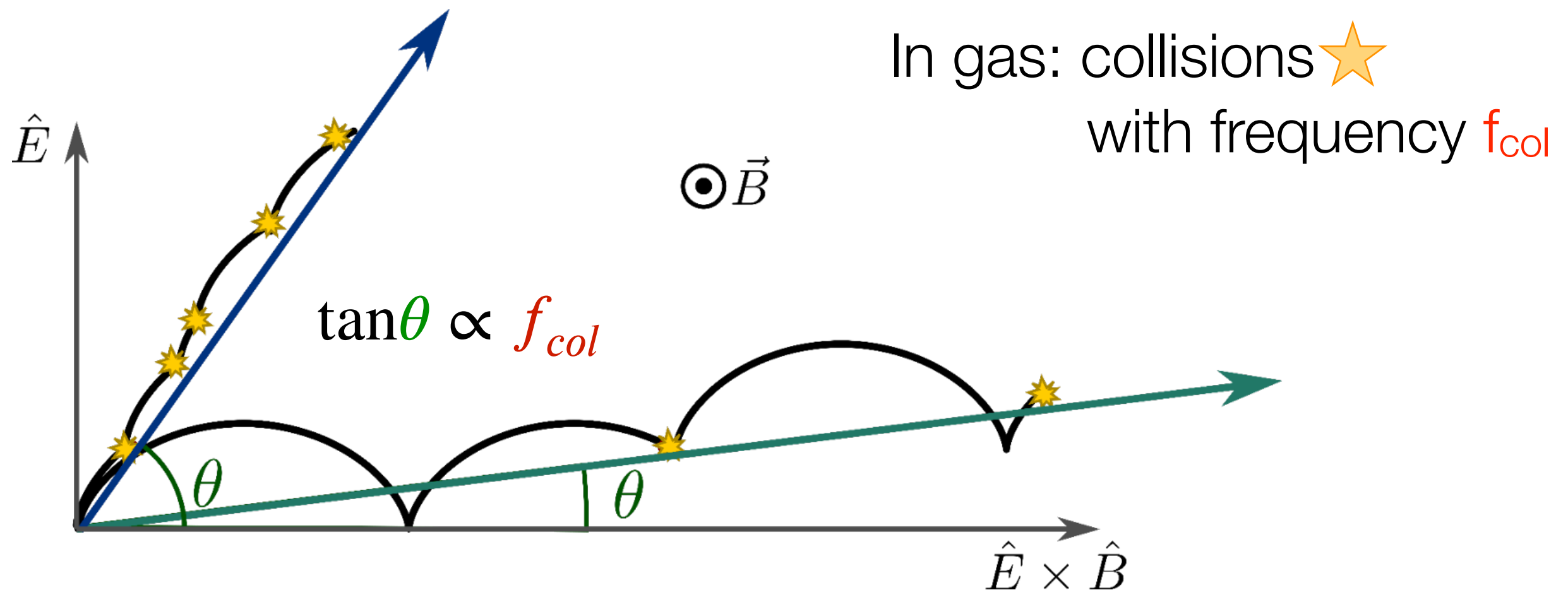
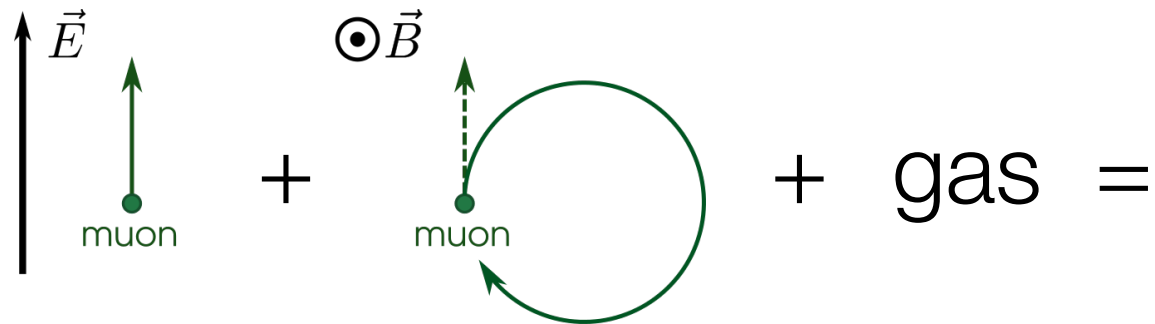
μ SR (solid state physics)

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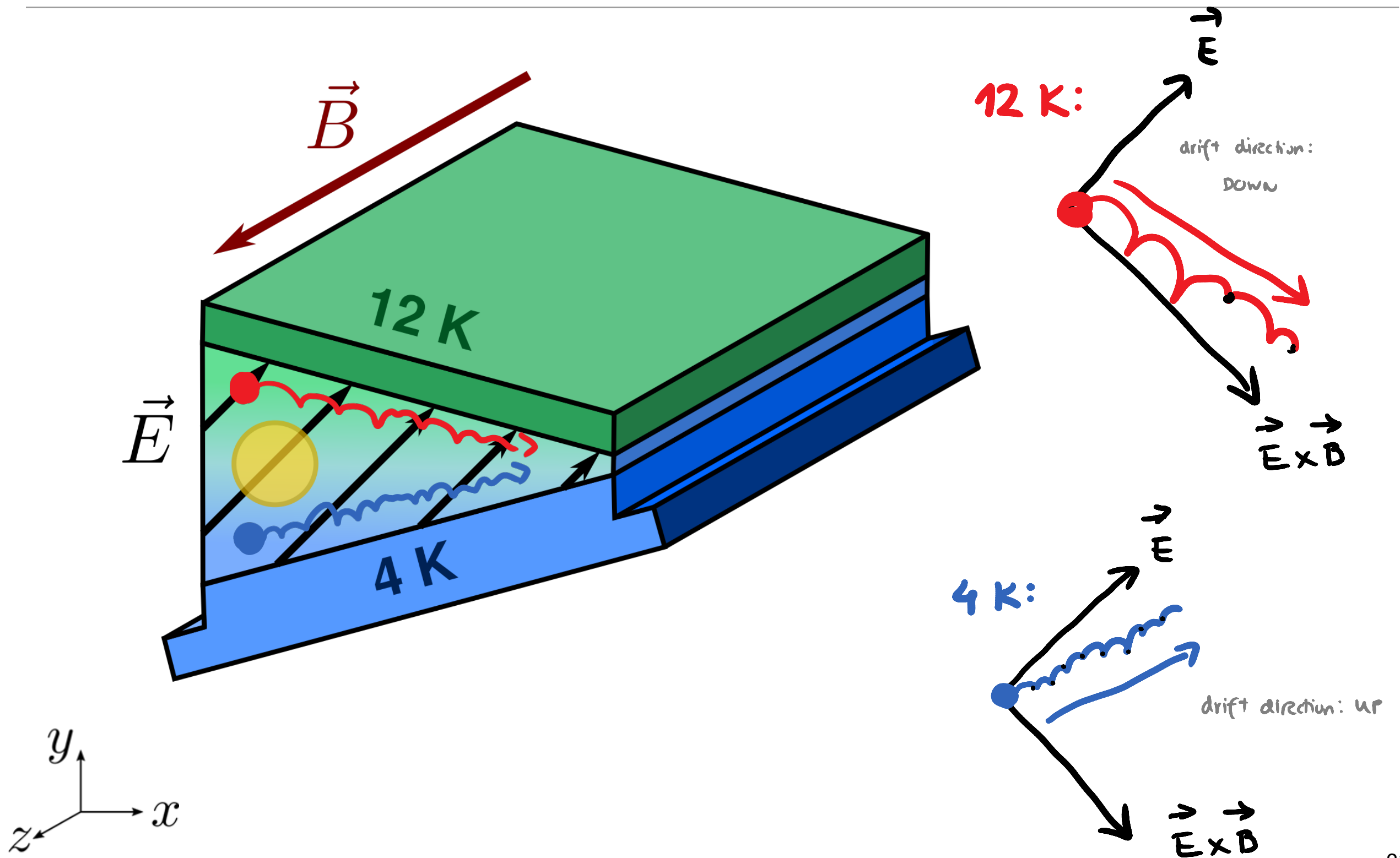
muon experiments (μ EDM, g-2...)



Trajectories in E and B field + gas

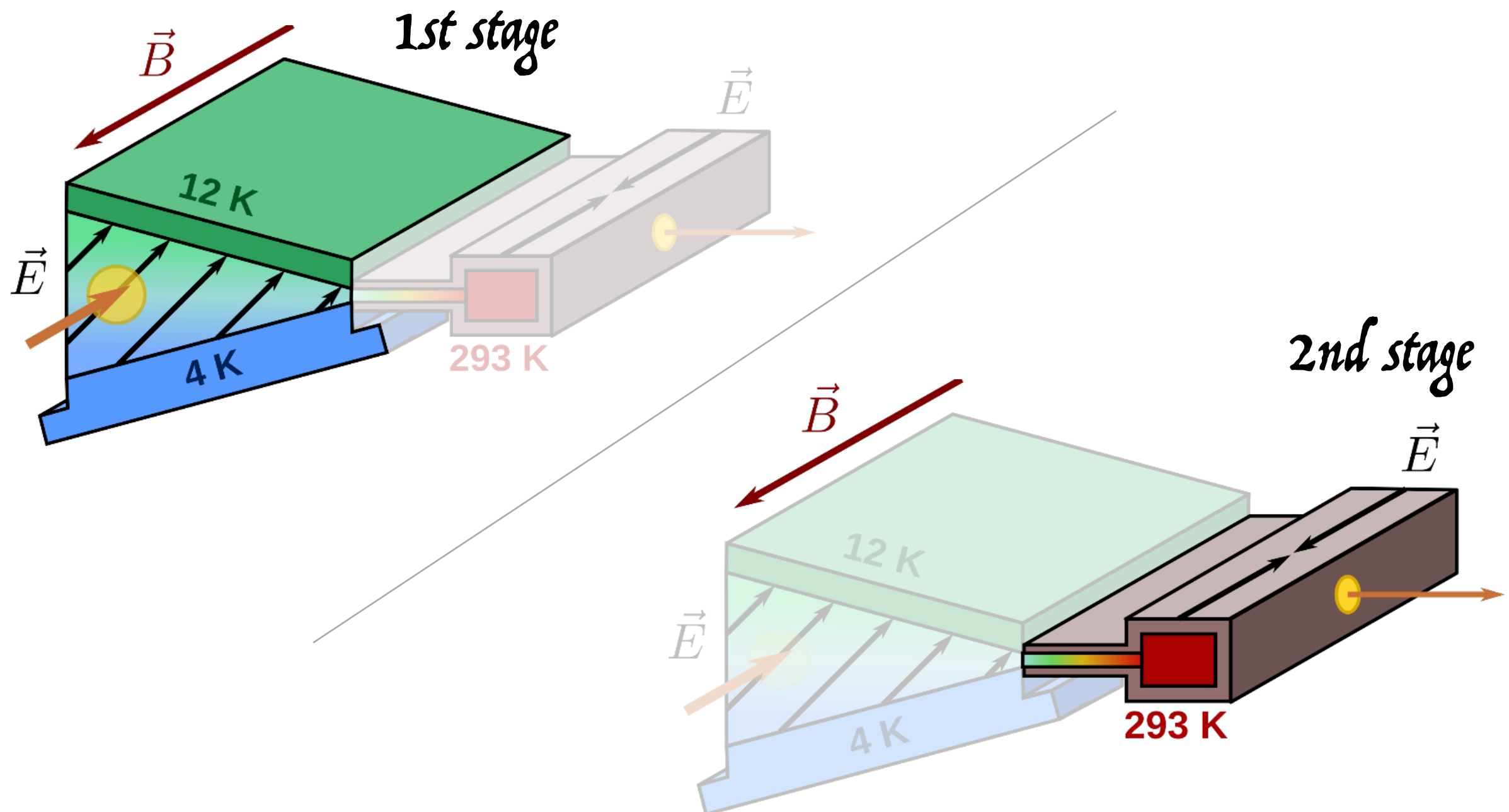


Working principle: 1st Stage

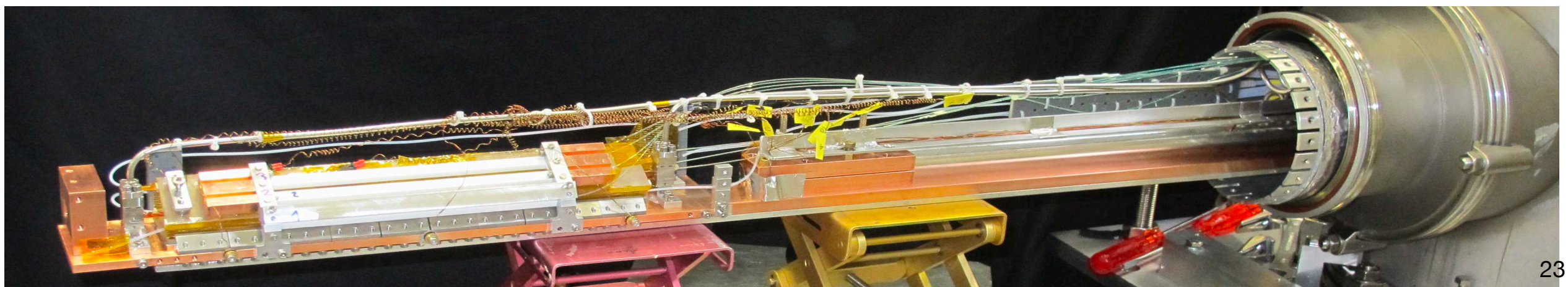
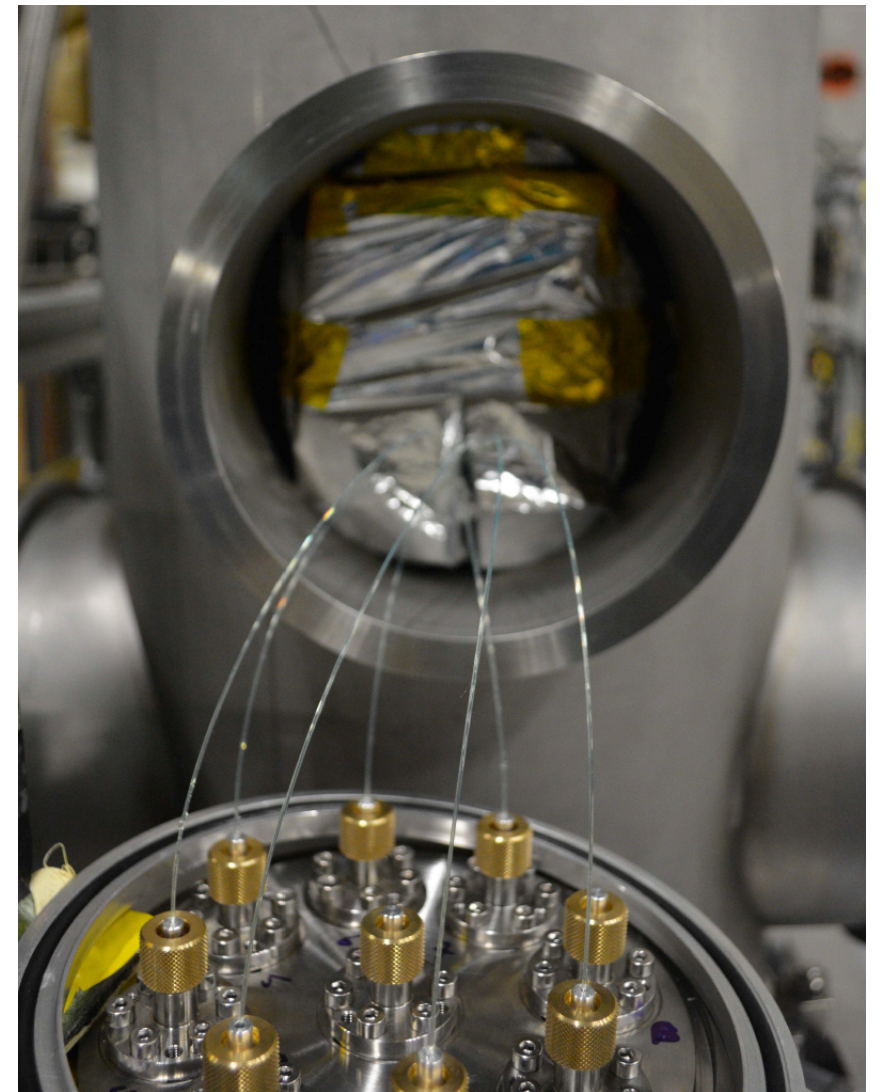
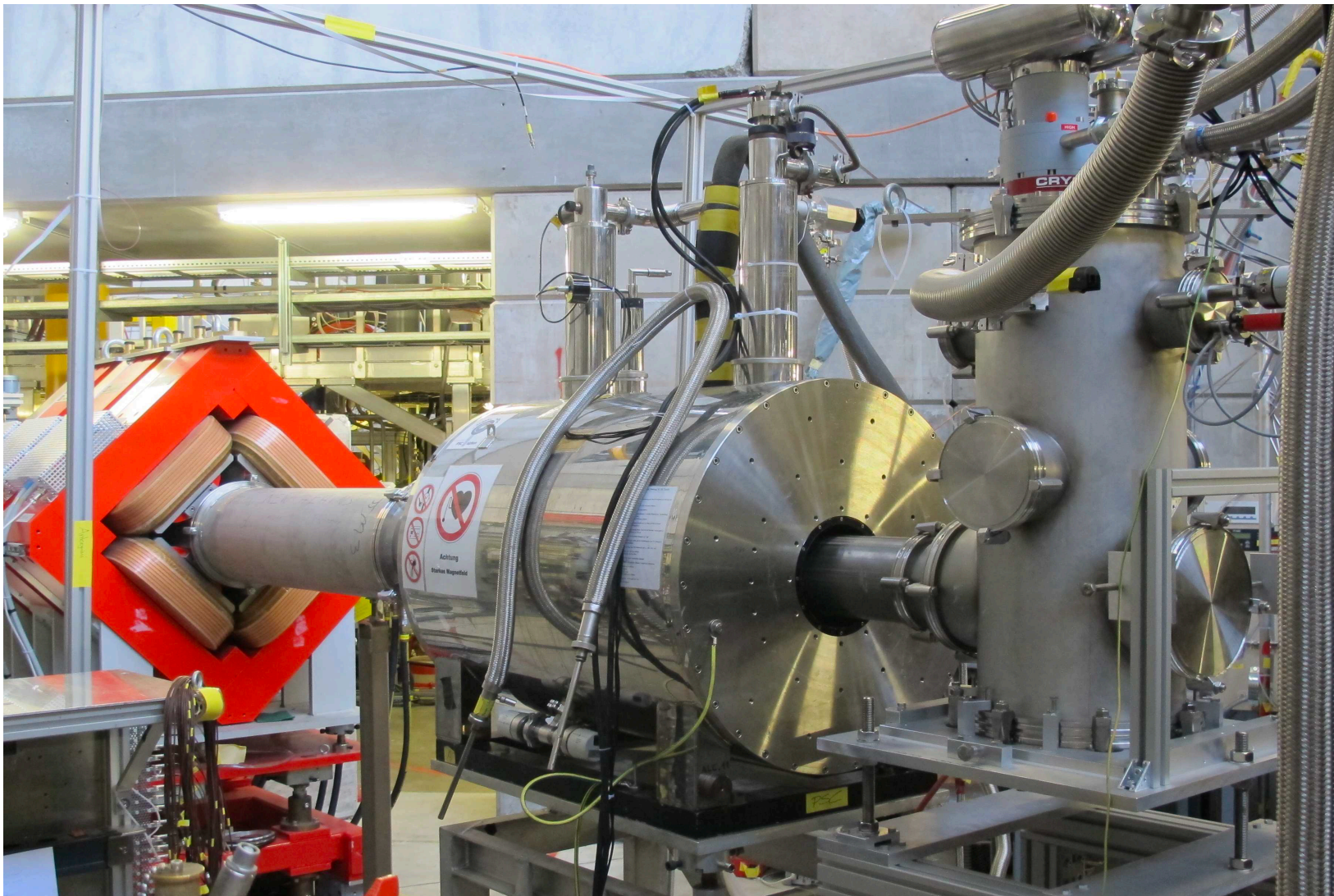


Experimental setup and results: 1st stage and 2 stage

- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**

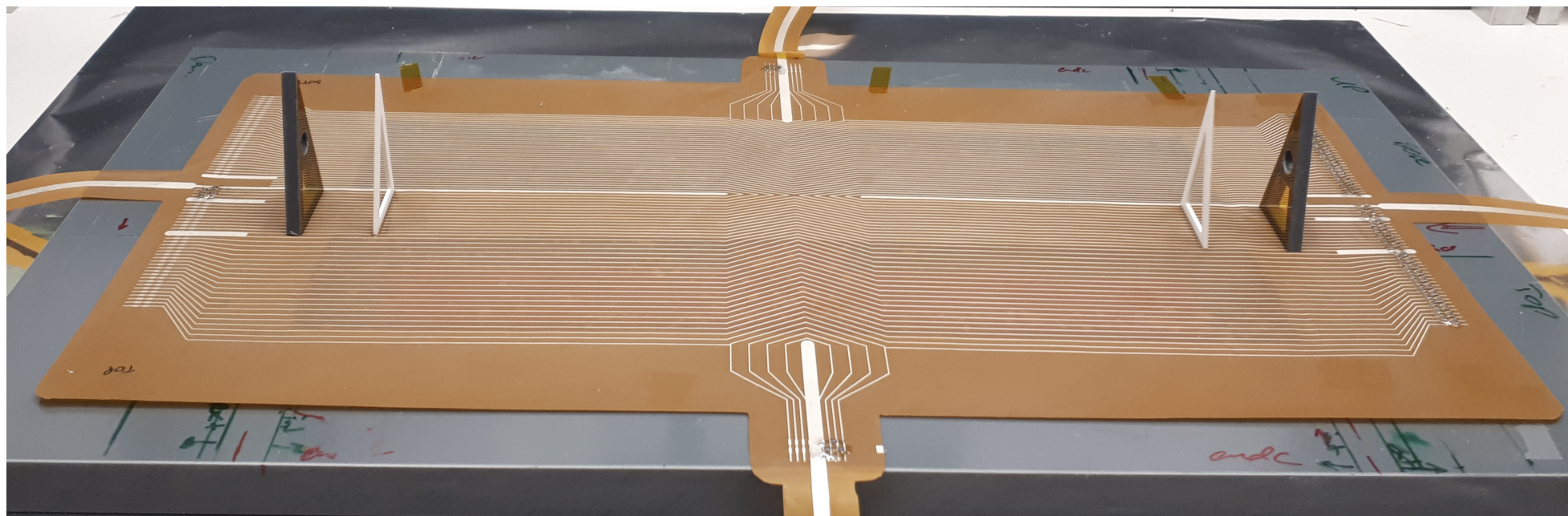
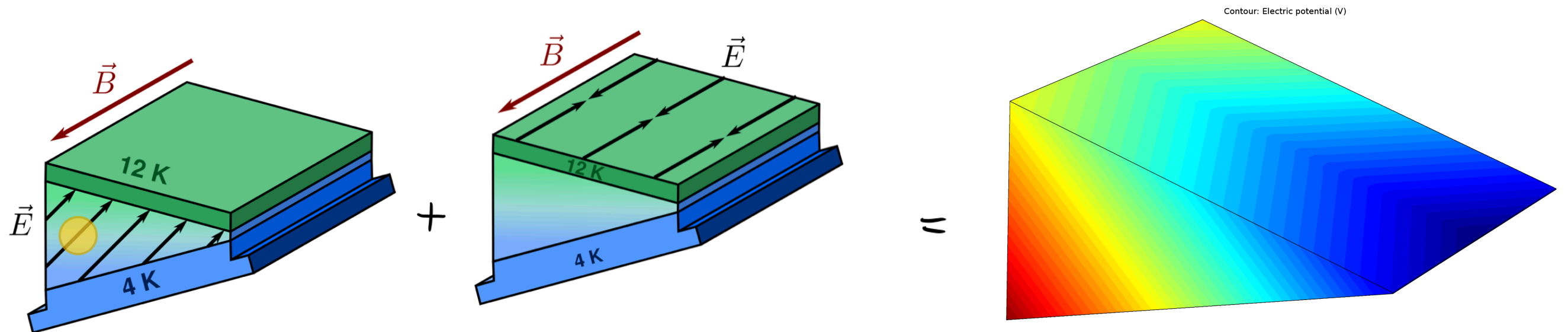


Experimental setup and results: 1st stage



The muCool project at PSI: Status

- 1st stage + 2nd stage
- **Next Step:** Extraction into vacuum



Outlook

- HiMB aims at surface high intensity muon beam **$O(10^{10} \text{ muon/s})$**
 - Initial simulations show that such rates are feasible
 - Target optimisation test: successfully done. Increase muon rate as expected.
 - Beam optics and investigations on proton beam modifications underway
- Put into perspective the target optimisation only, corresponding to **50%** of muon beam intensity gain, would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW** without the additional complications such ad increased energy and radiation deposition into the target and its surroundings
- If the same exercise is repeated put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**
- muCool aims at low energy high-brightness muon beam
- Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-3}**
- First two stages demonstrated independently
- Measurements and simulations agree
- Current development: combining two stages and extraction into the vacuum



Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

DC or Pulsed?

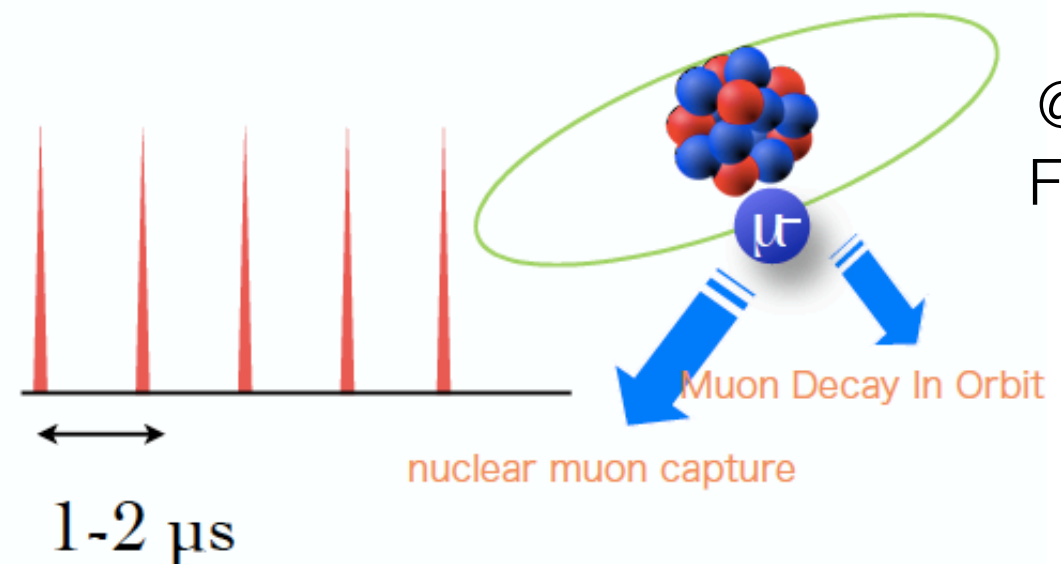
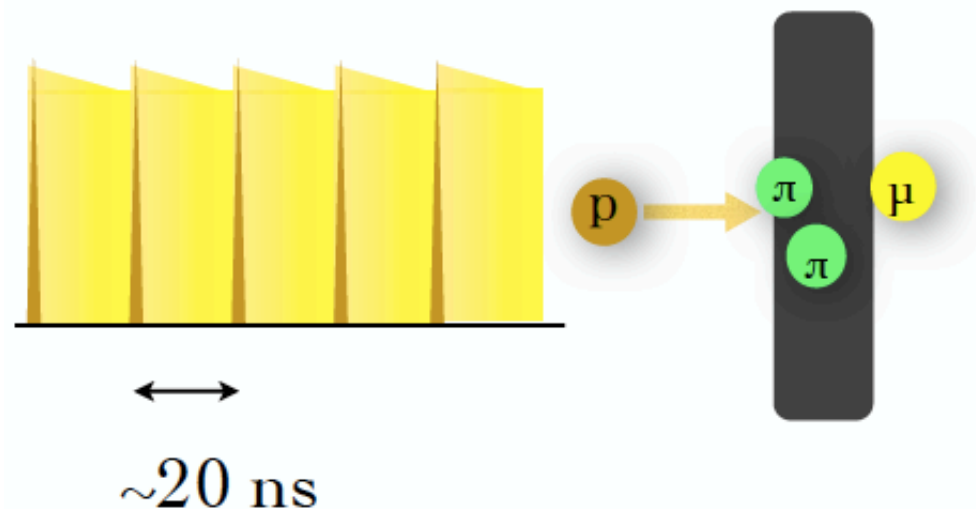
$I_{\text{beam}} \sim 10^8 - 10^{10} \mu/s$

- DC beam for coincidence experiments
- $\mu \rightarrow e \gamma, \mu \rightarrow e e e$

$I_{\text{beam}} \sim 10^{11} \mu/s$

- Pulse beam for non-coincidence experiments
- μ -e conversion

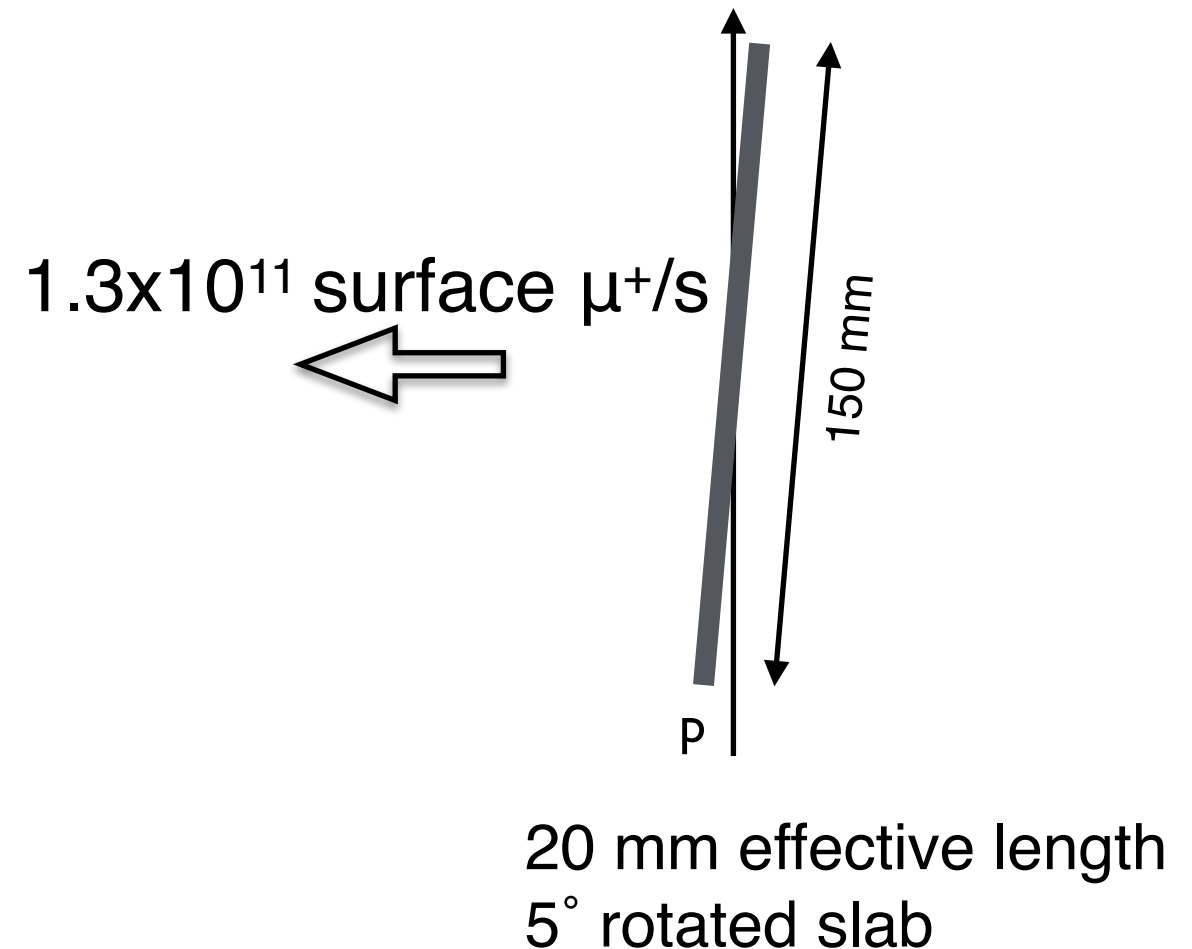
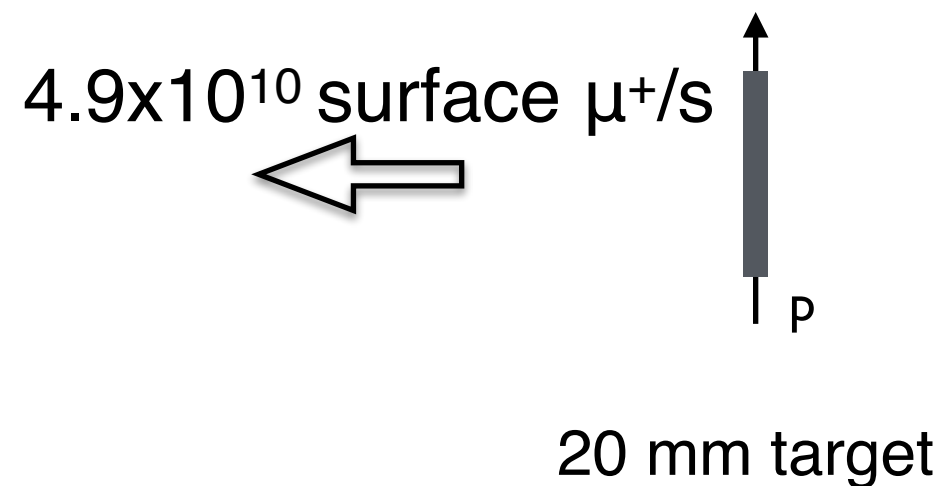
@ PSI



@ JPARC,
FERMILAB

Target geometry for new target M*

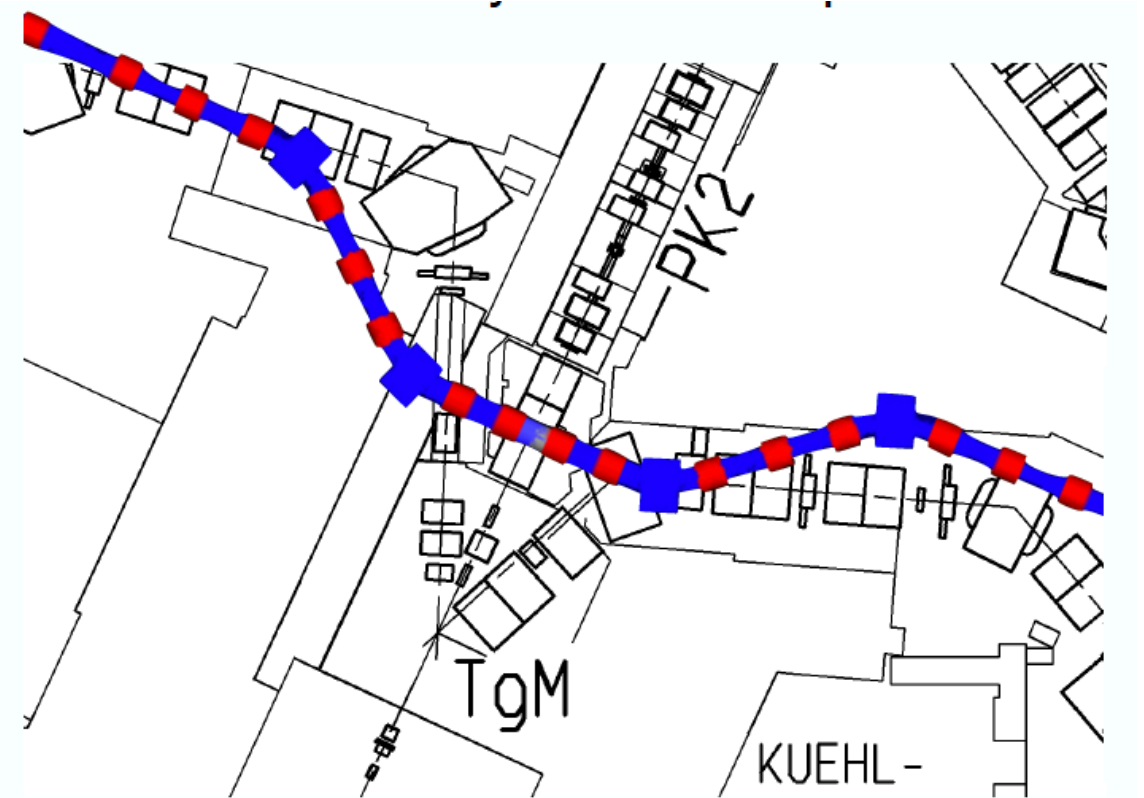
- Change current 5 mm TgM for 20 mm TgM*
- 20 mm rotated slab target as efficient as Target E



ToDo

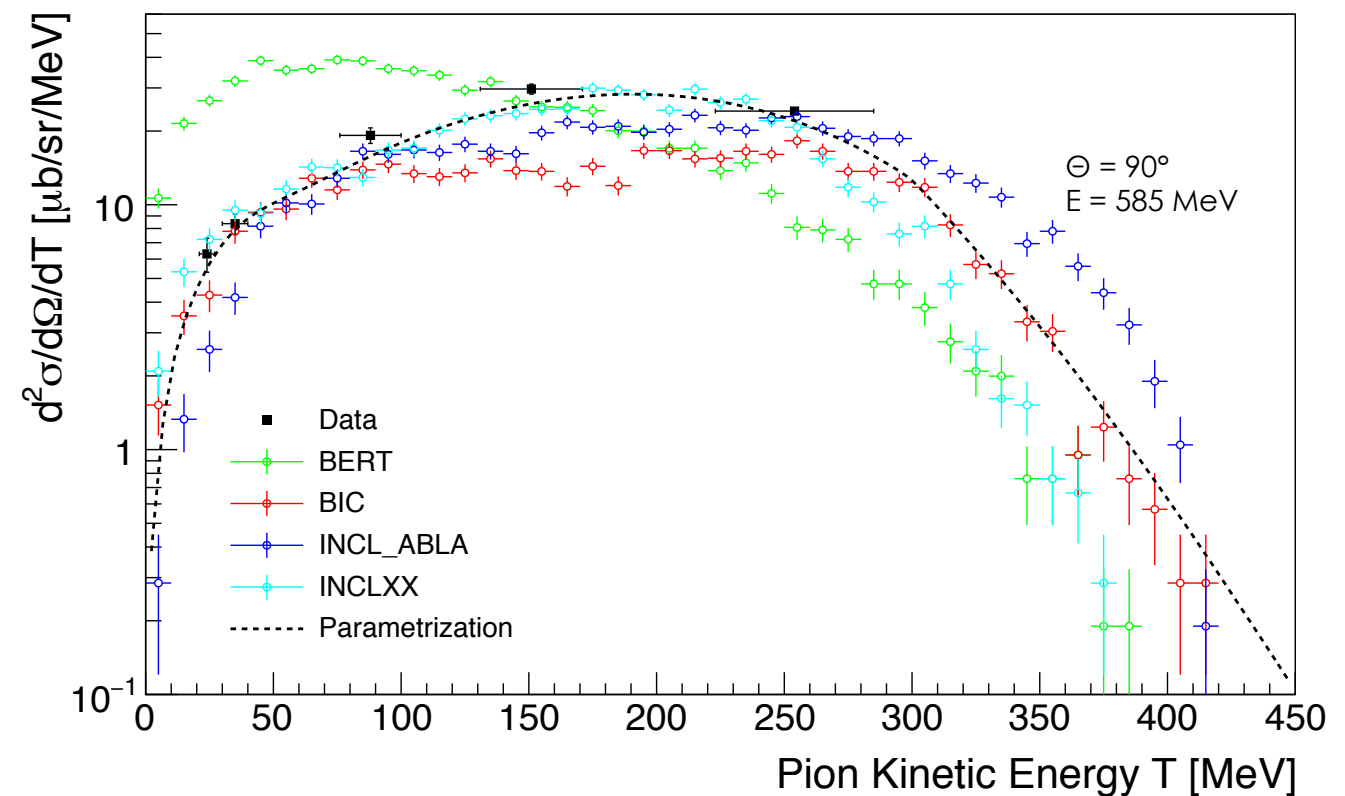
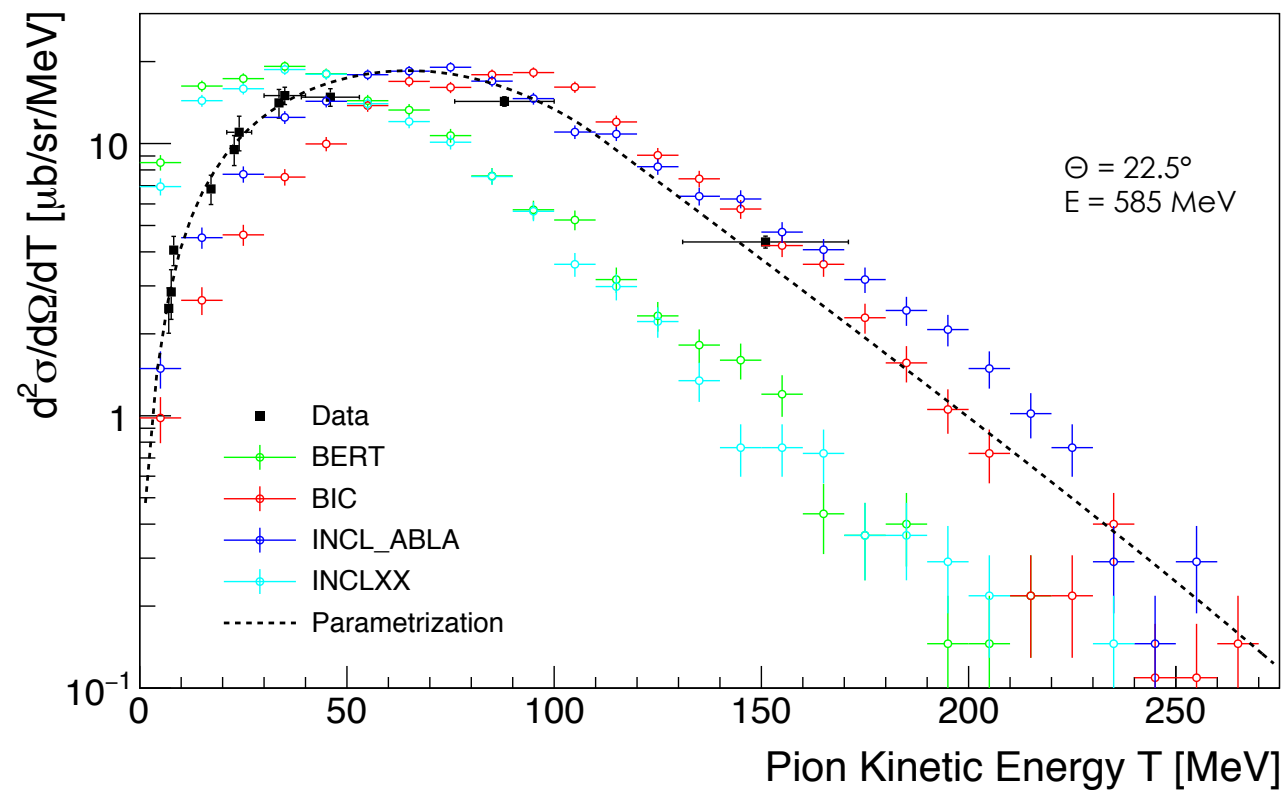
- Optimization of capturing
- Optimize final focussing
- Iterative Beam line optimization and implementation of beam monitoring and particle separator locations with max. transmission
- Minimize shielding modifications
- Particle separation
- Investigate impact on proton beam properties
- Study extraction angle
- Determine new target location
- Disposal of highly radioactive waste
- Study Mu3e setup phase space acceptance and optimize final focus properties
- Find solution with current users of Target M

Schematic of the layout in the experimental hall



HiMB Simulation

- Geant4 pion production cross sections not optimised for low energies
- Implemented our own pion production cross section into Geant4/G4beamline based on measured data and two available parametrizations (**HiMB model**)
- Valid for all pion energies, proton energies < 1000 MeV, all angles and all materials
- Reliable results at 10% level



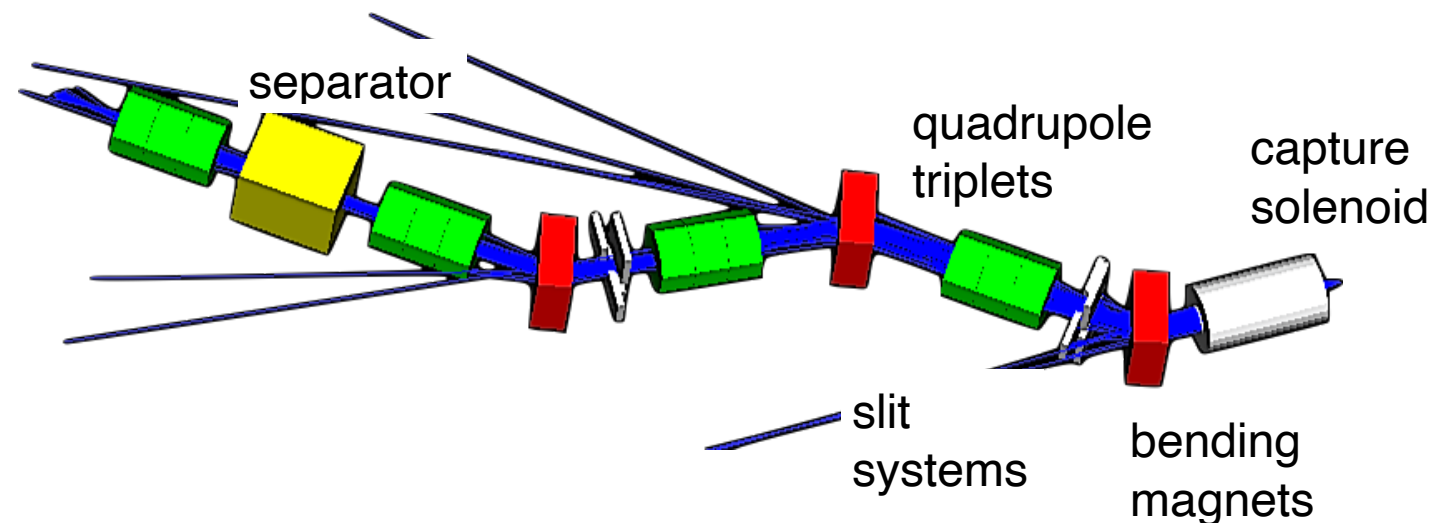
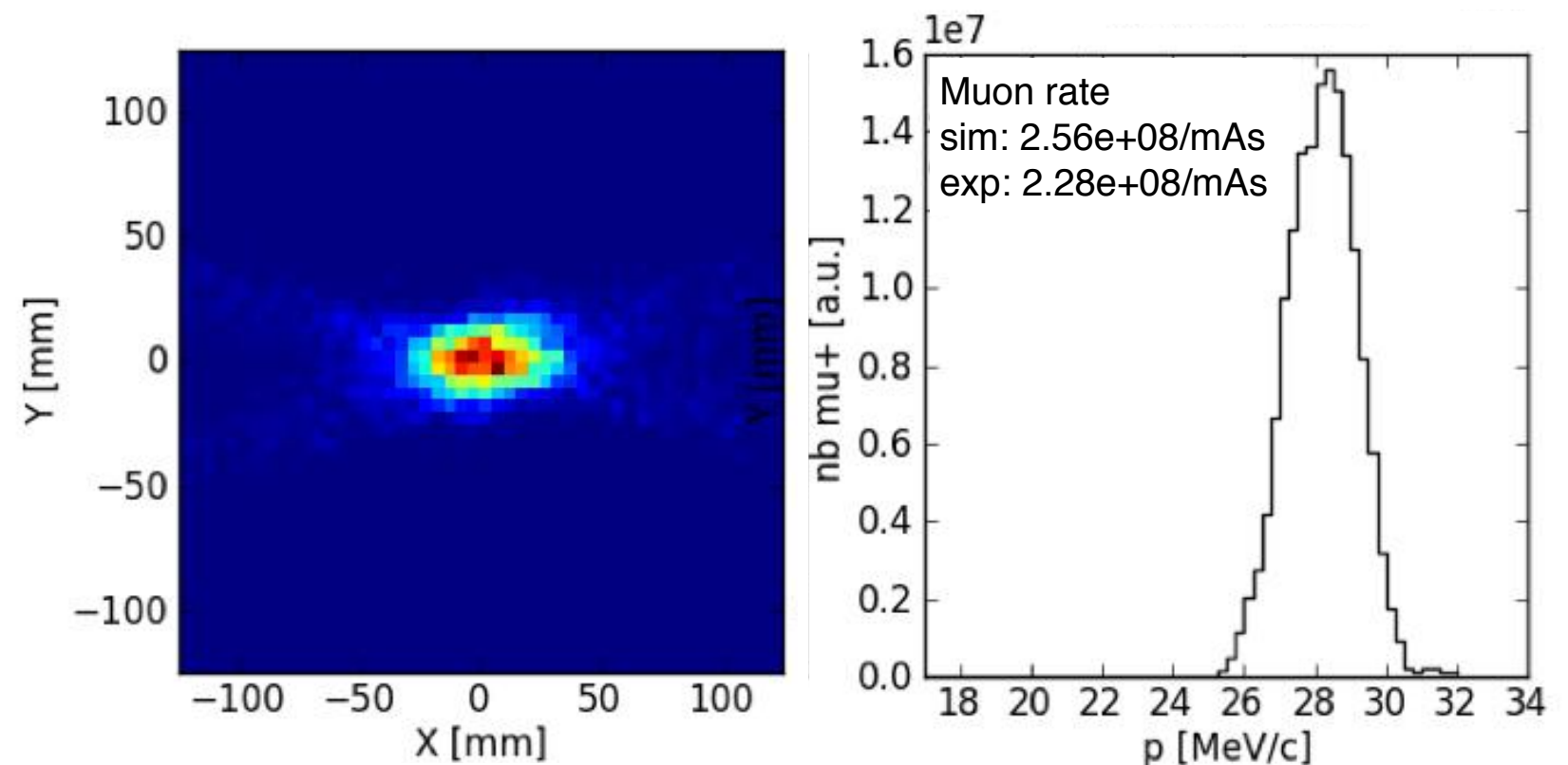
R. L. Burman and E. S. Smith, Los Alamos Tech. Report LA-11502-MS (1989)

R. Frosch, J. Löffler, and C. Wigger, PSI Tech. Report TM-11-92-01 (1992)

F. Berg et al., Phys. Rev. Accel. Beams **19**, 024701 (2016)

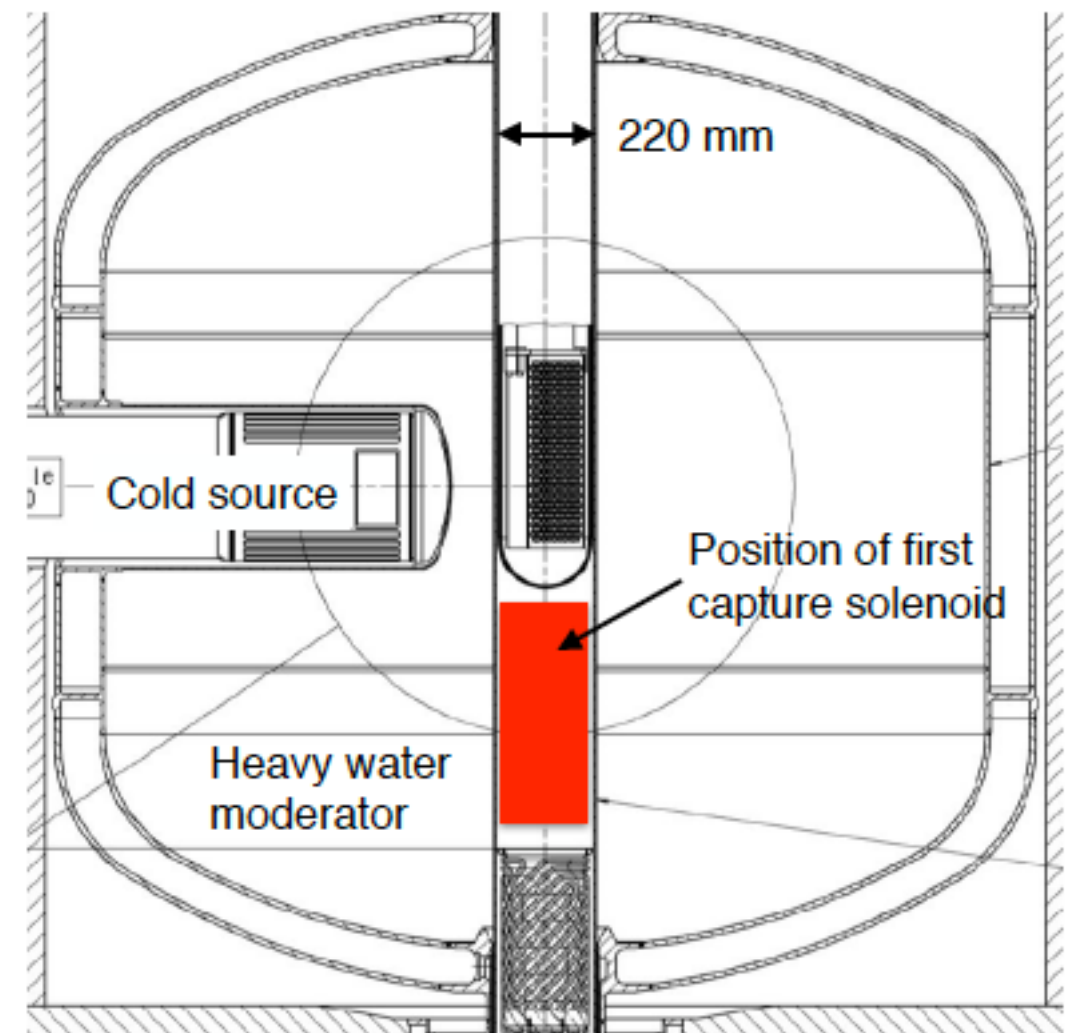
HiMB model validation

- Full simulation of μ E4 and π E5 beam lines starting from proton beam
- Detailed field maps available for all elements
- Very good agreement between simulation and measurements



Initial HiMB concept: @SINQ

- Source simulation (below safety window):
 9×10^{10} surface- μ^+ /s @ 1.7 mA I_p
- Profit from stopping of full beam
- Residual proton beam (~ 1 MW) dumped on SINQ
- Replace existing quadrupoles with solenoids:
 - Preserve proton beam footprint
 - Capture backward travelling surface muons
- Extract muons in Dipole fringe field
- Backward travelling pions stopped in beam window
- Capturing turned out to be difficult :
 - Large phase space (divergence & 'source' extent)
 - Capture solenoid aperture needed to be increased, but constrained by moderator tank
- High radiation level close to target
- Due these constraints and after several iterations with different capturing elements:
 - **Not enough captures muons to make an high intensity beam**
 - **Alternative solution: HiMB @ EH**



Optimization of standard production targets

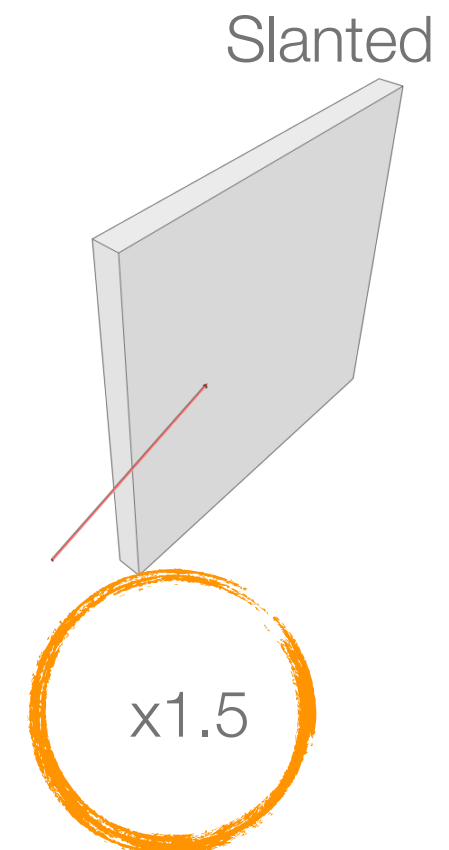
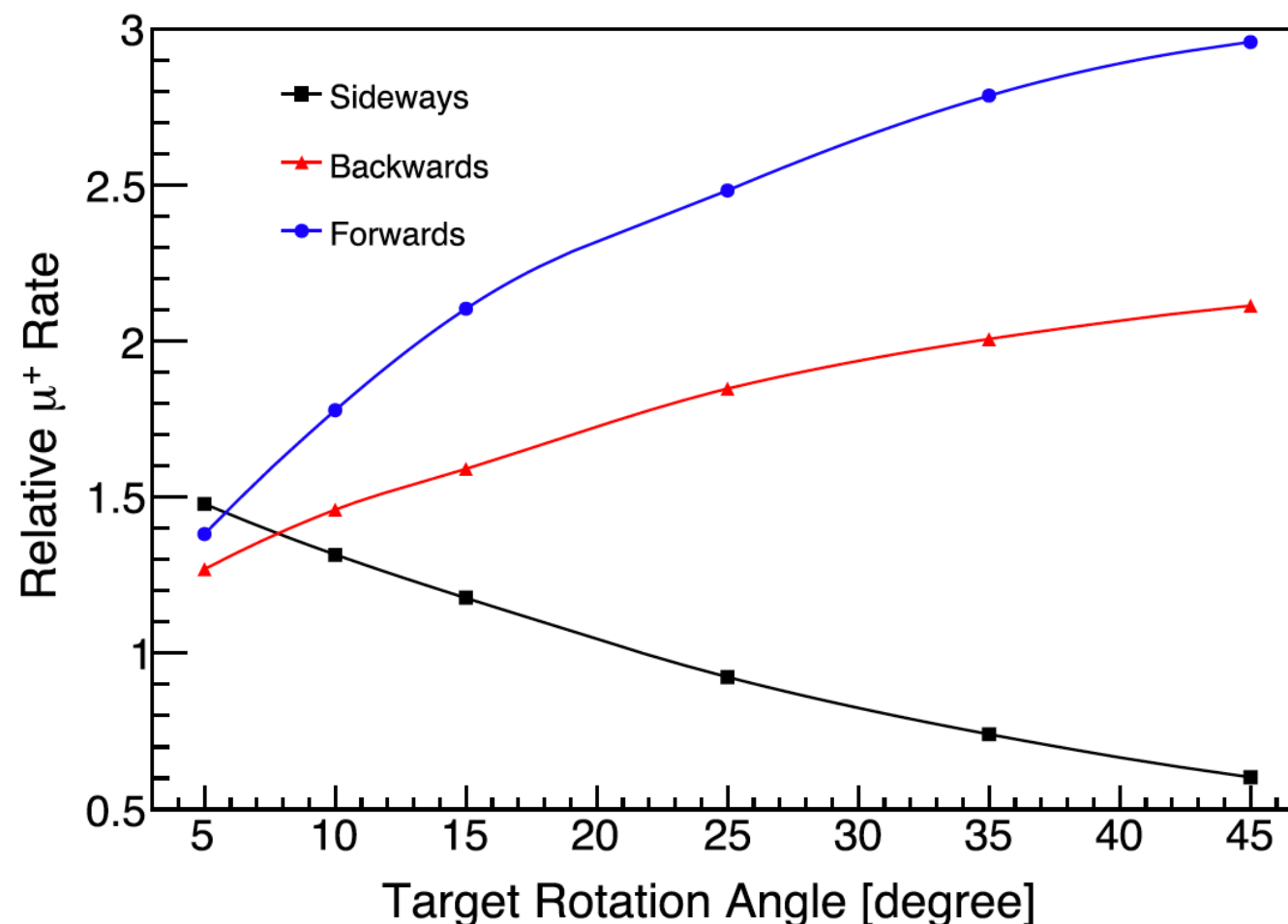
- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface
- **Target geometry**
 - Comparison studies of different target geometries: **TgE for different lengths**

Surface muon rate

Length [mm]	Upstream	Downstream	Side
10	1.4×10^{10}	9.0×10^9	1.8×10^{10}
20	1.6×10^{10}	1.2×10^{10}	5.1×10^{10}
30	1.9×10^{10}	1.1×10^{10}	8.5×10^{10}
40	1.8×10^{10}	1.1×10^{10}	1.2×10^{11}
60	1.8×10^{10}	1.2×10^{10}	2.1×10^{11}

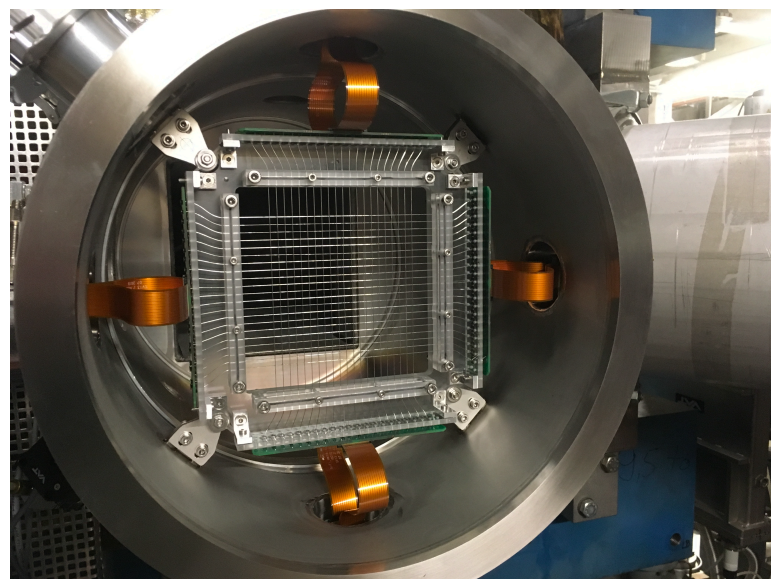
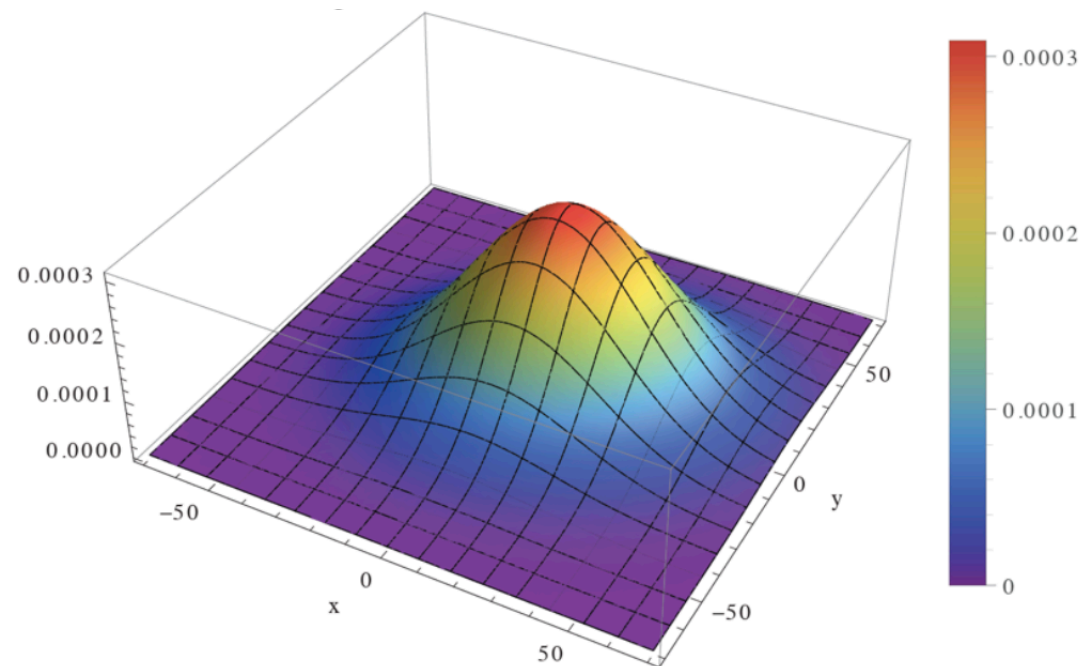
Optimization of standard production targets

- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface
- **Target geometry**
 - Comparison studies of different target geometries: **Different rotation angles**
 - Enhancements normalised to standard target



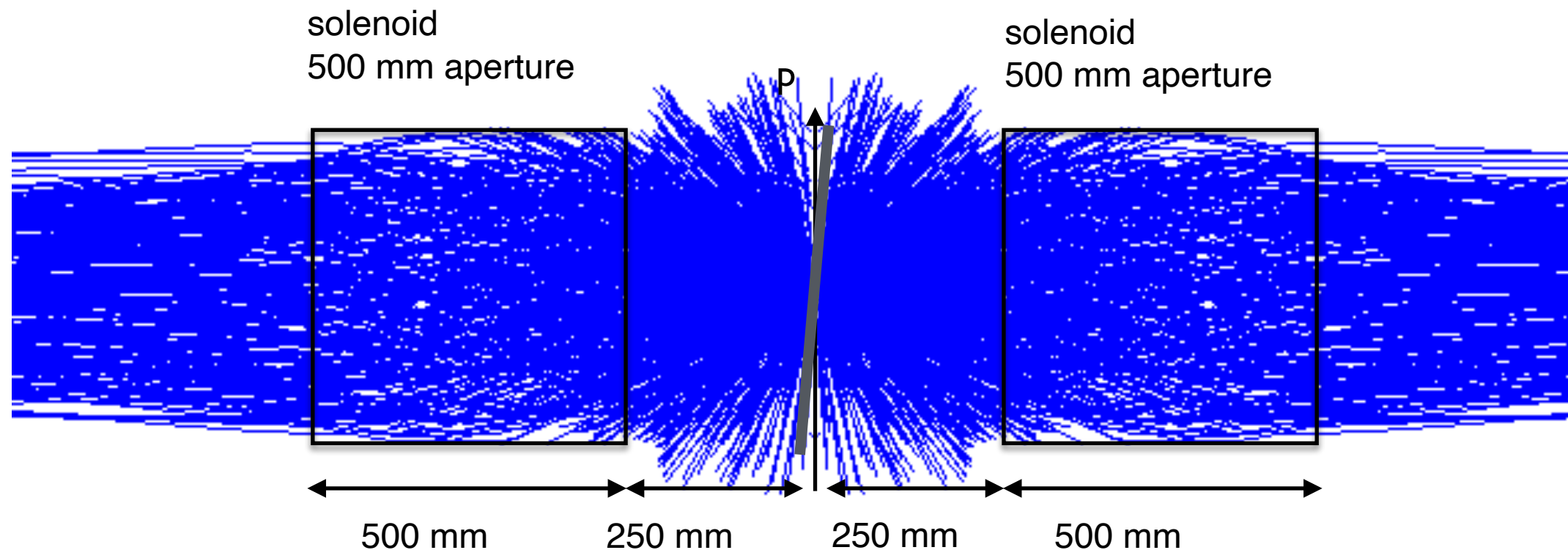
Slanted target: 2019 test Results

- Two independent detectors
 - SciFi: $0.5 \times 0.5 \text{ mm}^2$ scintillating fibers coupled to SiPMs to form a grid
 - Pill: (diam.) 2 mm x (length) 2 mm scintillator coupled to Hamamatsu R9880U-110 photomultiplier



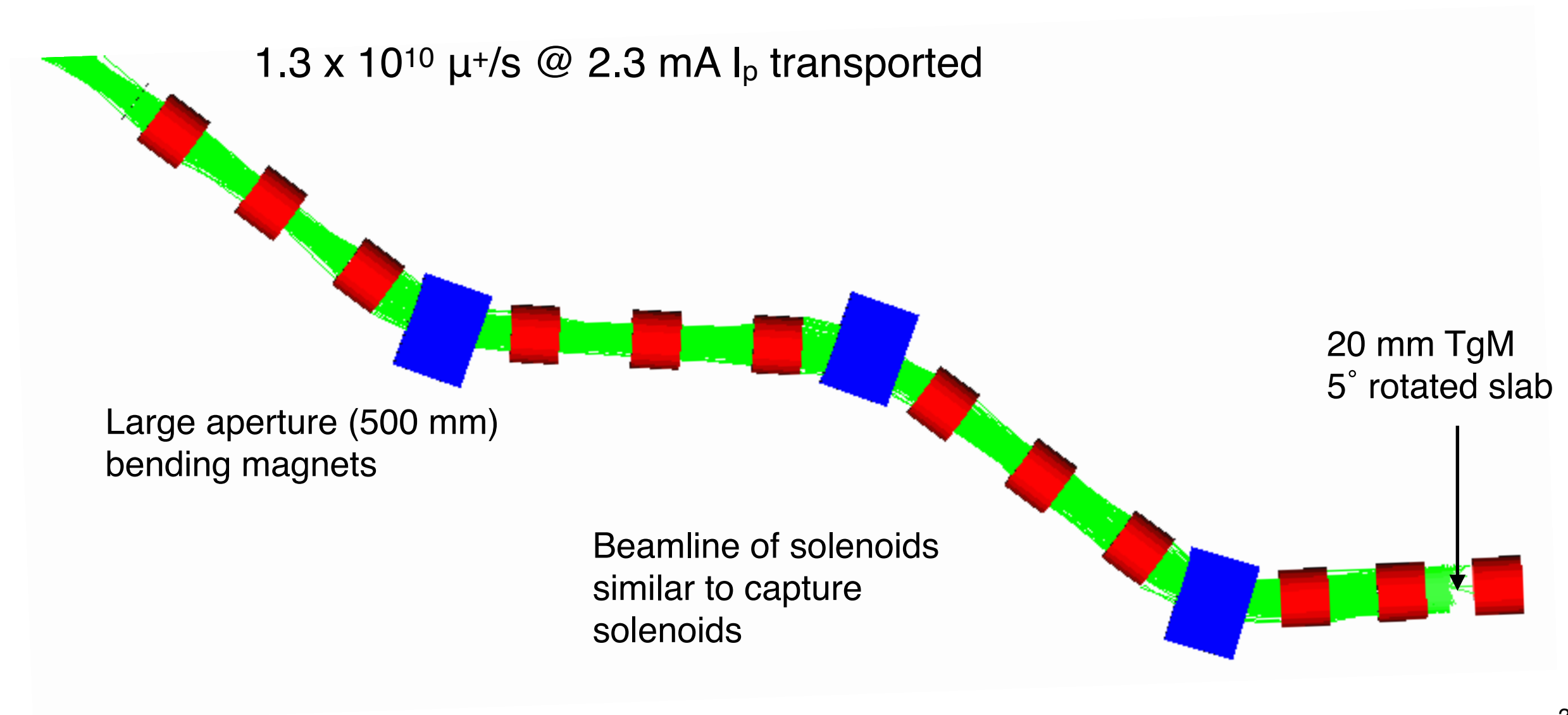
Split capture solenoids

- Two normal-conducting, radiation-hard solenoids close to target to capture surface muons
- Central field of solenoids ~ 0.35 T
- Field at target ~ 0.1 T



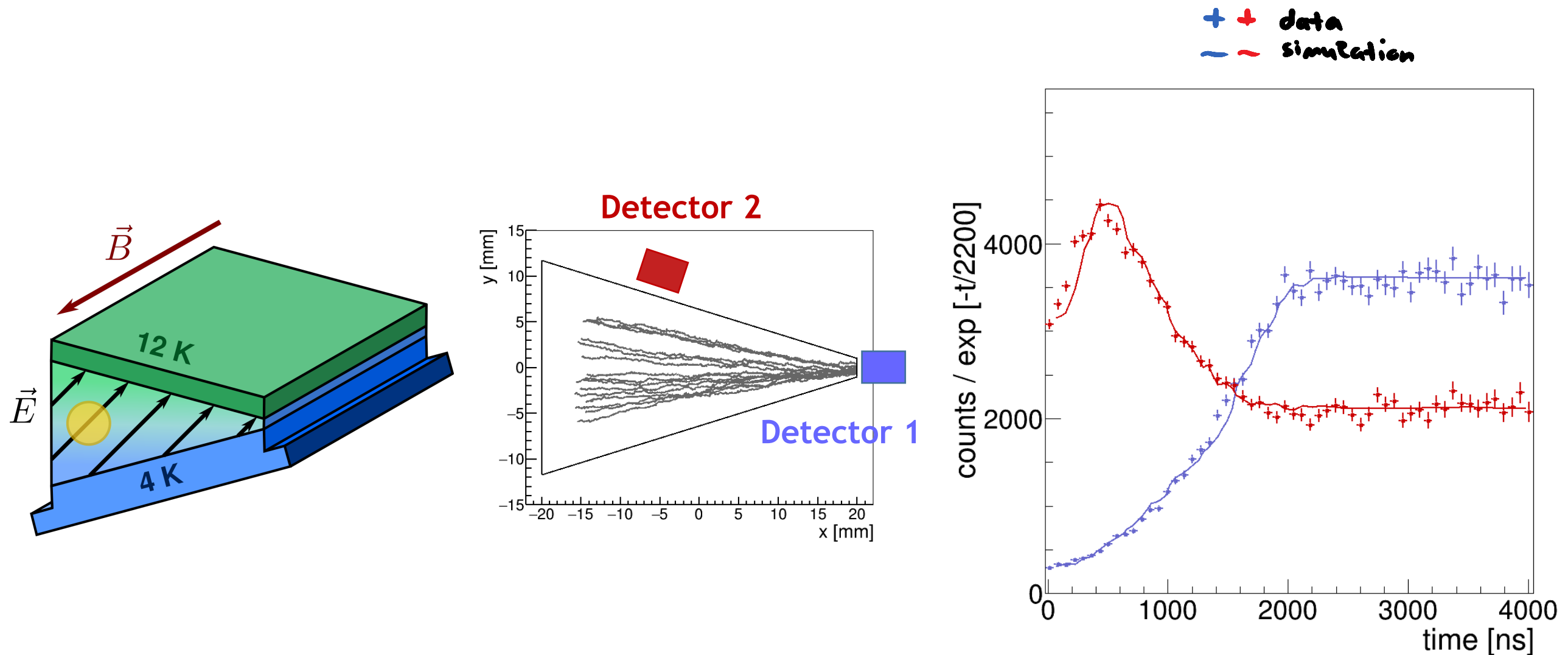
Solenoid beam line

- First version of beam optics showing that large number of muons can be transported.
- Almost parallel beam, no focus, no separator, ...
- Final beam optics under development



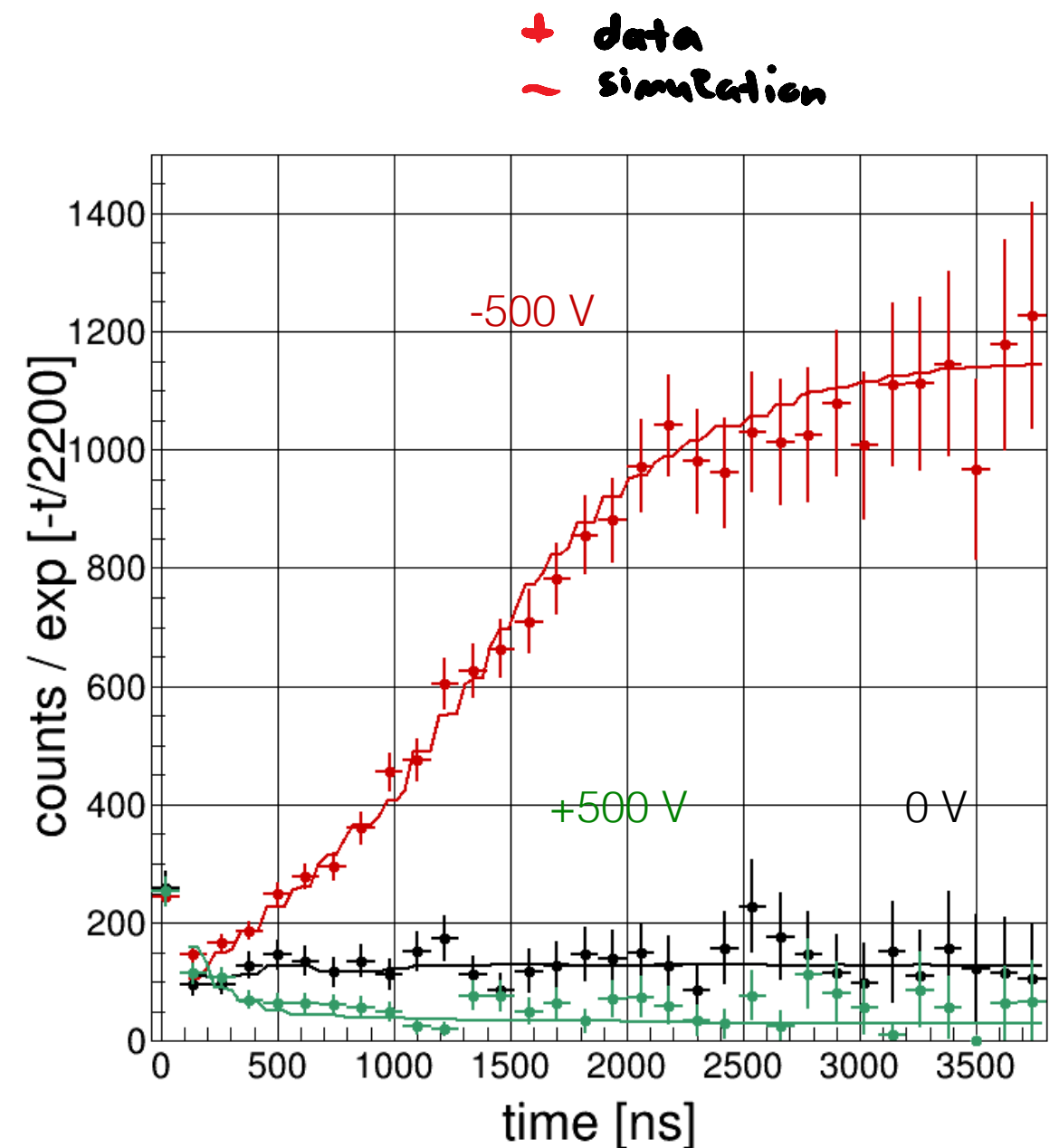
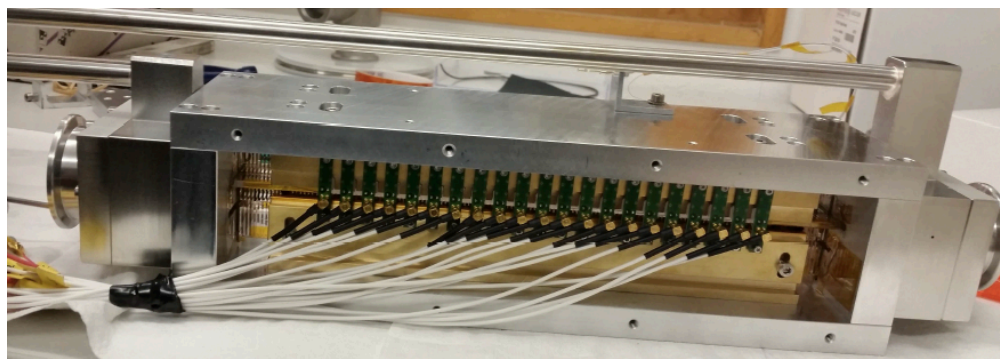
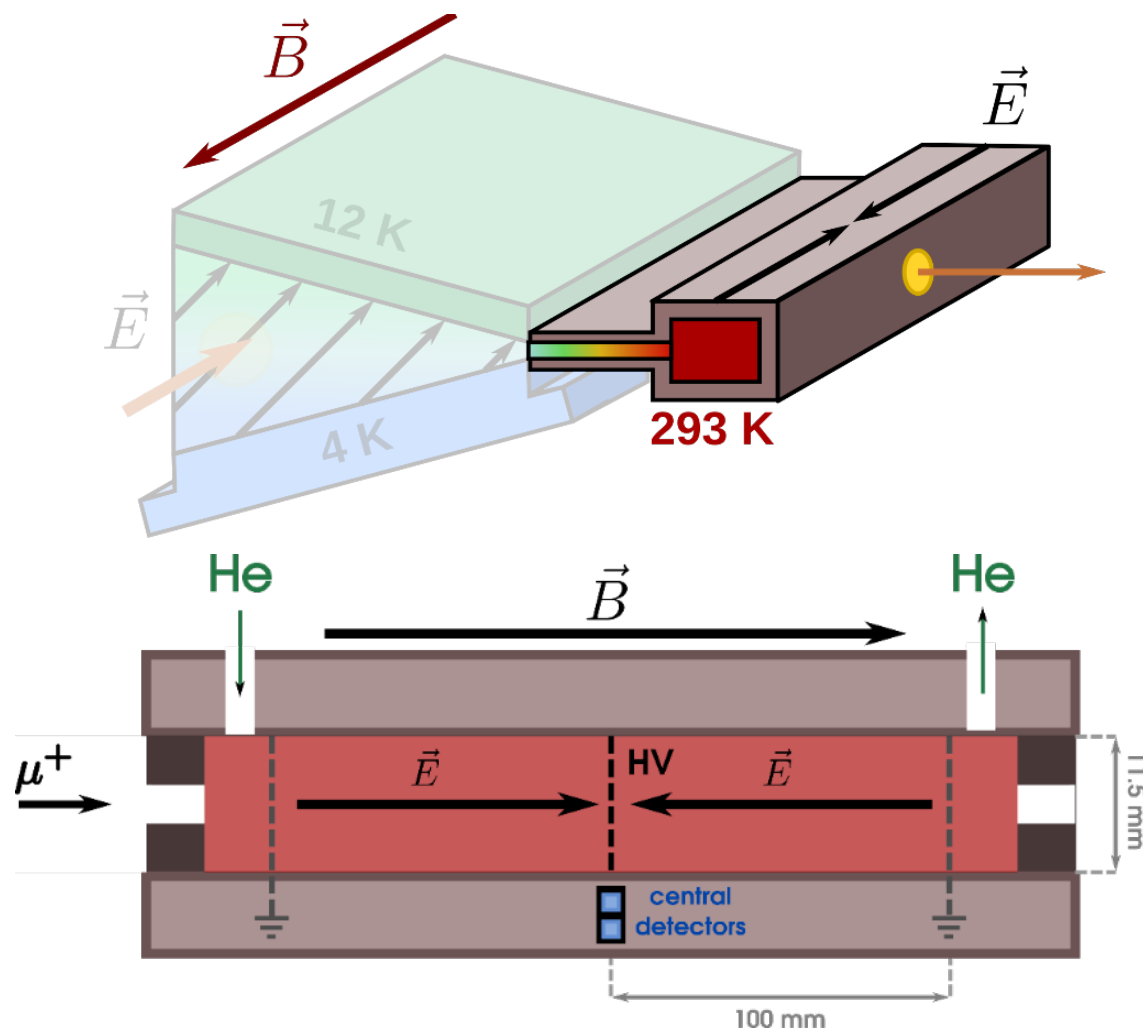
Experimental setup and results: 1st stage

- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**



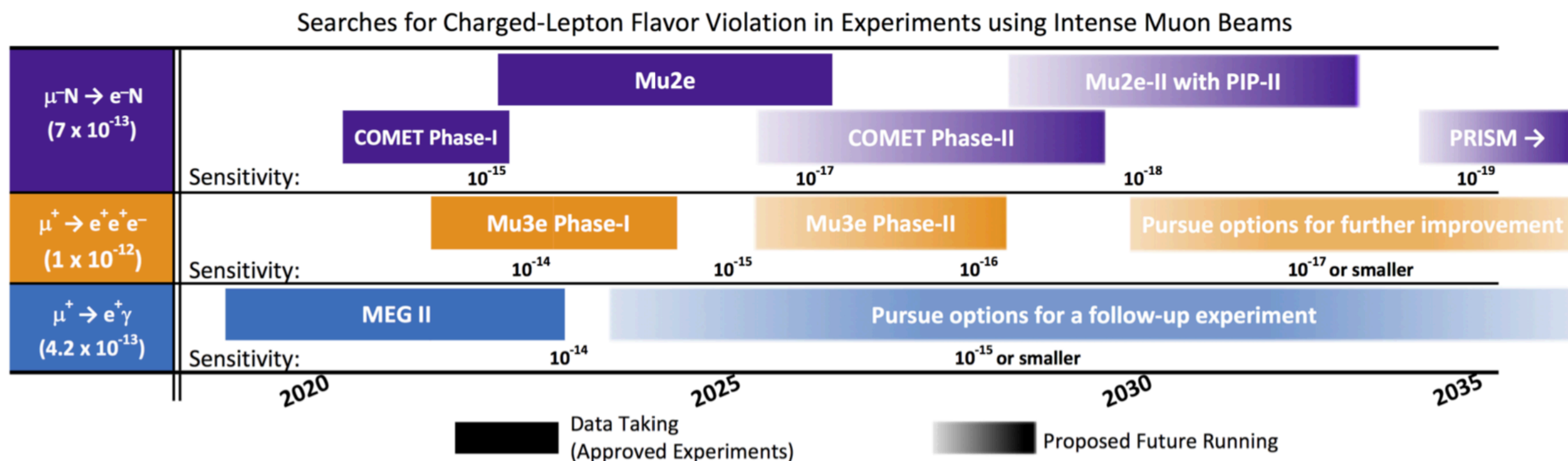
Experimental setup and results: 2nd stage

- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**



Final remarks

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- **cLFV remains one of the most exciting place where to search for new physics**
- Submitted inputs to the European Strategy Committee

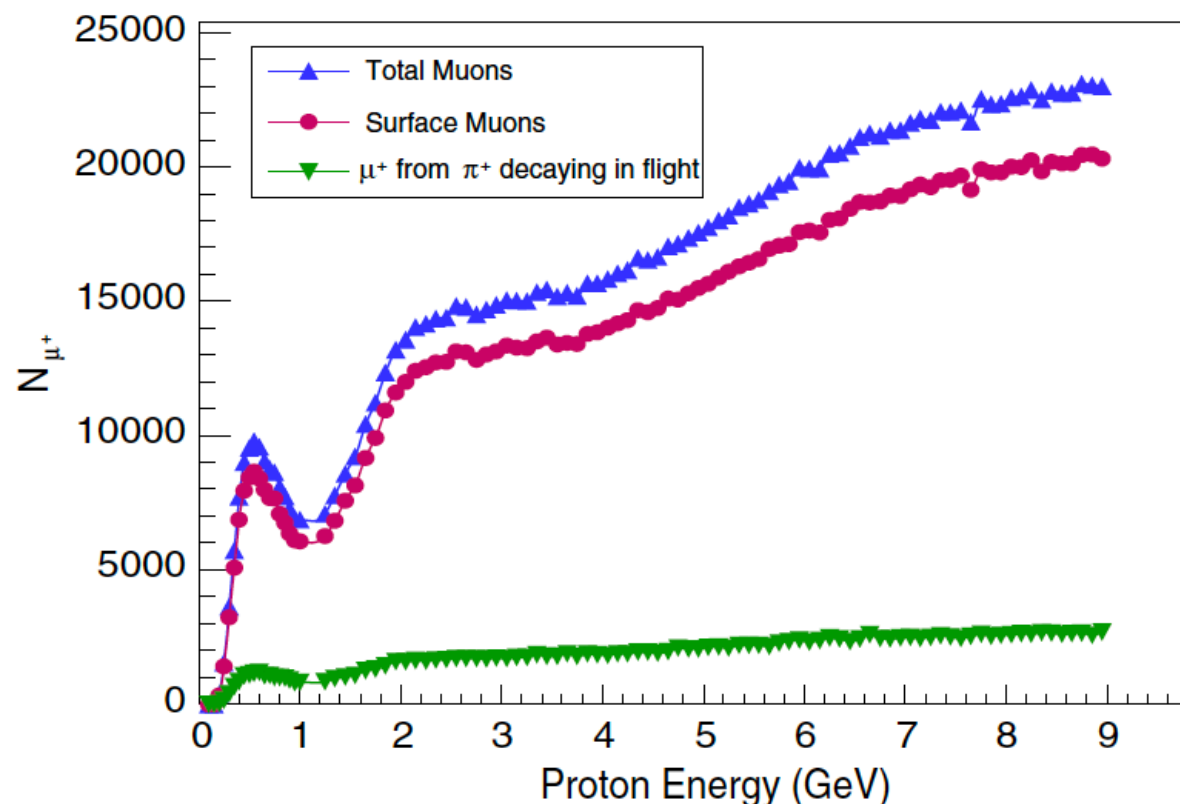


Thanks for your attention!

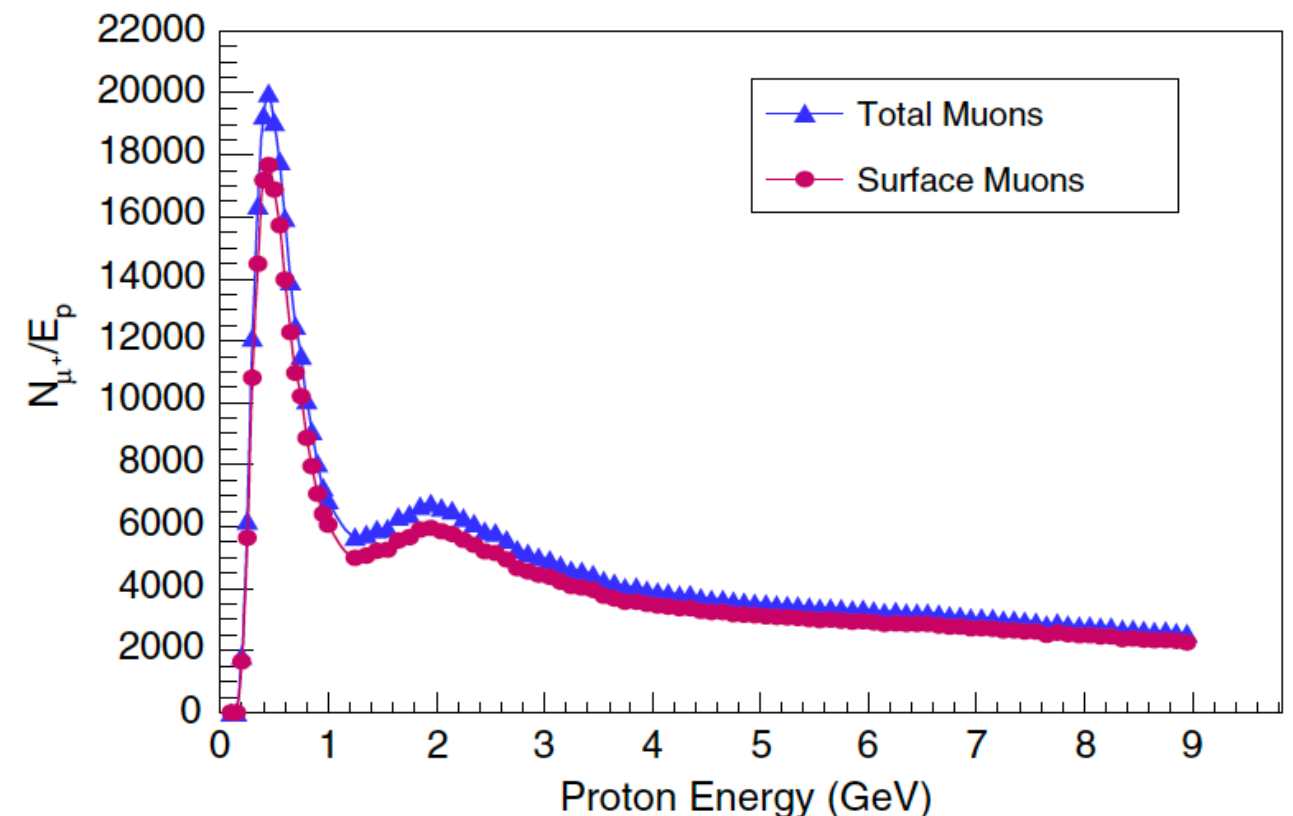
Optimal surface muon production

- **BUNGAU** et al., Phys. Rev. ST Accel. BEAMS **16**, 014701 (2013)
- Target: graphite
- Simulation validation: ISIS data
- For standalone muon facility: 500 MeV proton energy is the optimal energy

Variation of muon yield with proton energy at higher energies



Normalization of the muon yield to the proton energy



Muon production via pion decay

- Single pion production at 290 MeV proton energy (LAB)
- Low-energy muon beam lines typically tuned to surface- μ^+ at ~ 28 MeV/c
- Note: surface $-\mu \rightarrow$ polarized positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons

